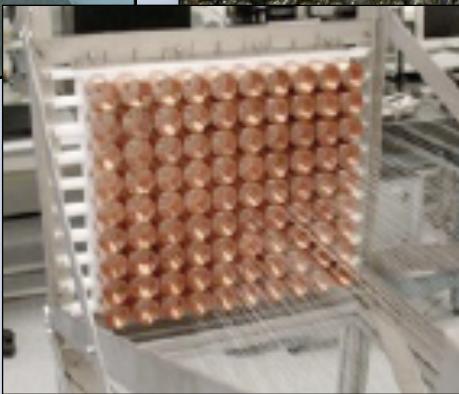
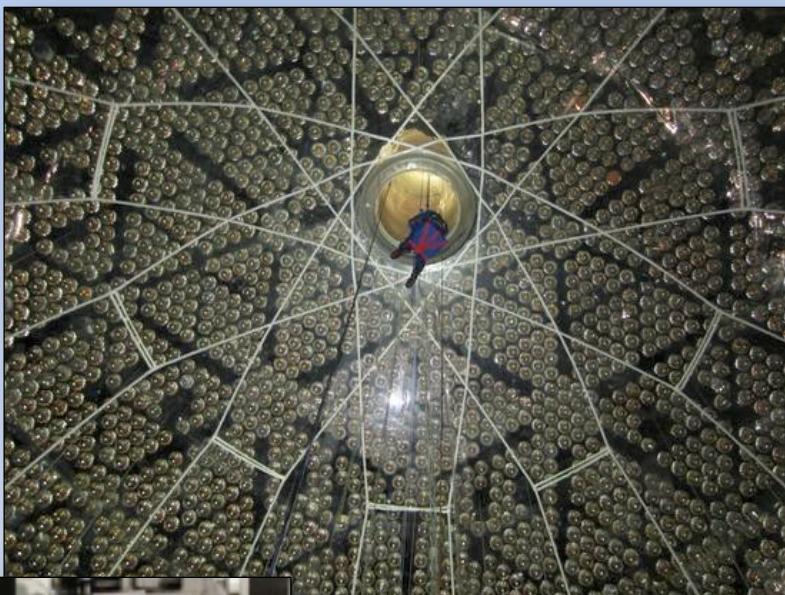
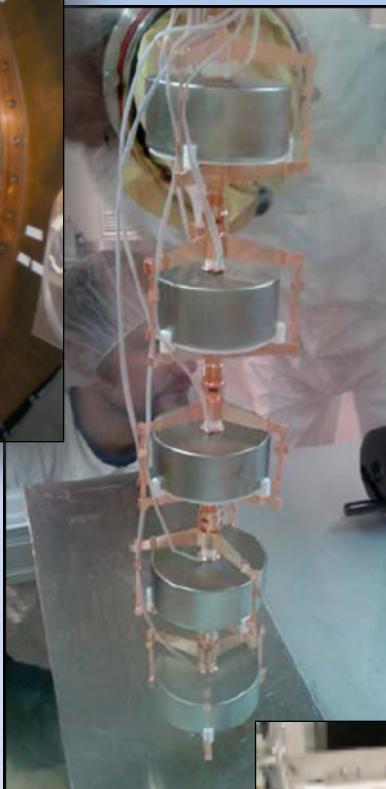
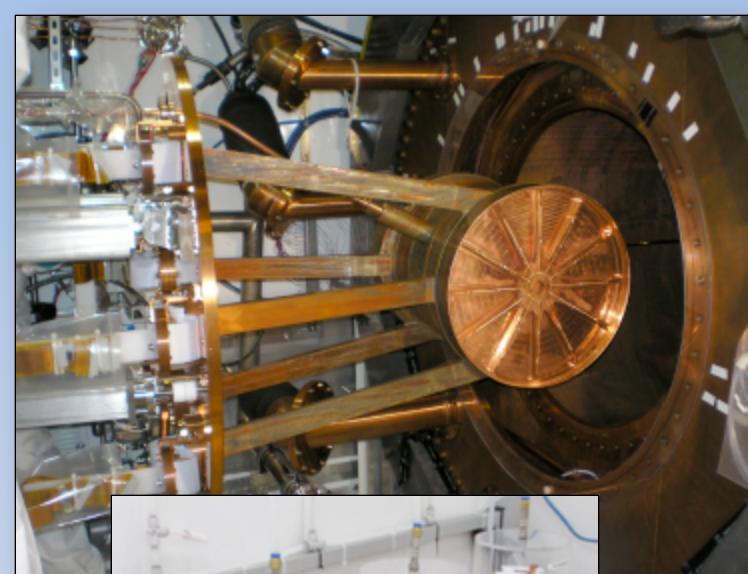


Double Beta Decay: Current Status



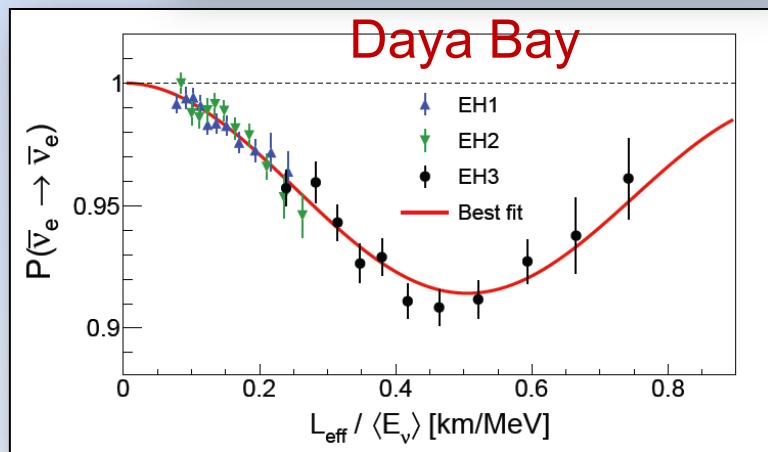
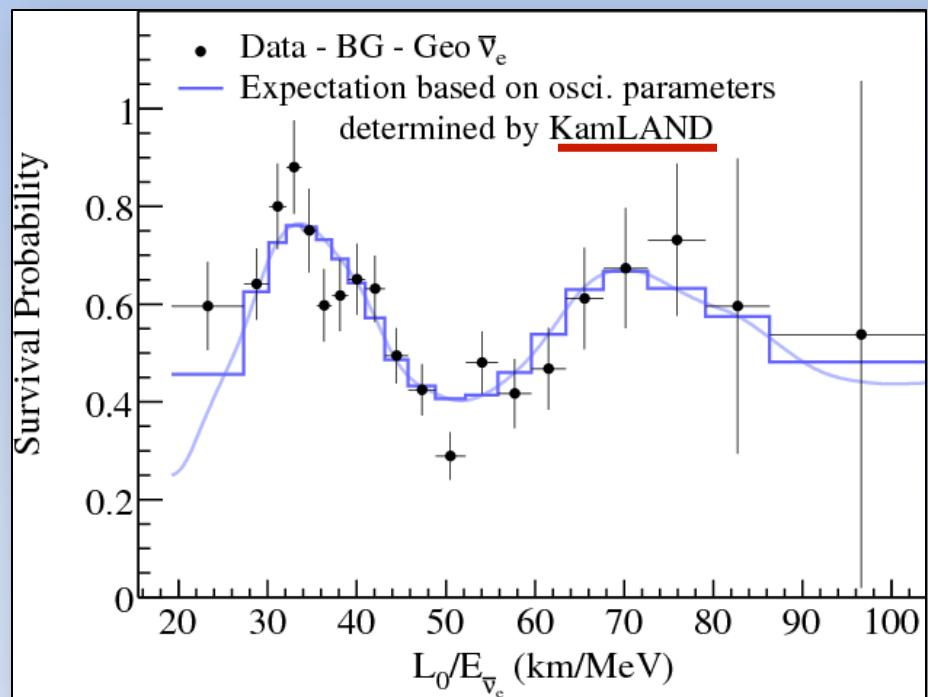
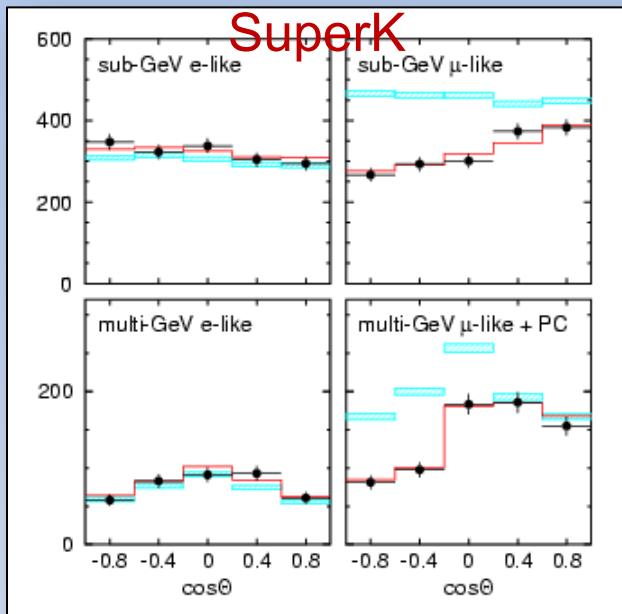
BNL Colloquium
April 25, 2017

R. D. McKeown
Jefferson Lab
College of William and Mary

Outline

- Neutrino Mass
- Double Beta Decay
- The experimental challenge
- Techniques
- R&D program
- Future prospects

Neutrino Oscillations ($m_\nu \neq 0$)



Measure:

- $|\Delta m_{ij}^2|$
- θ_{ij}

Three Flavor Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} \nu_1 \\ e^{i\alpha_2/2} \nu_2 \\ \nu_3 \end{pmatrix}$$

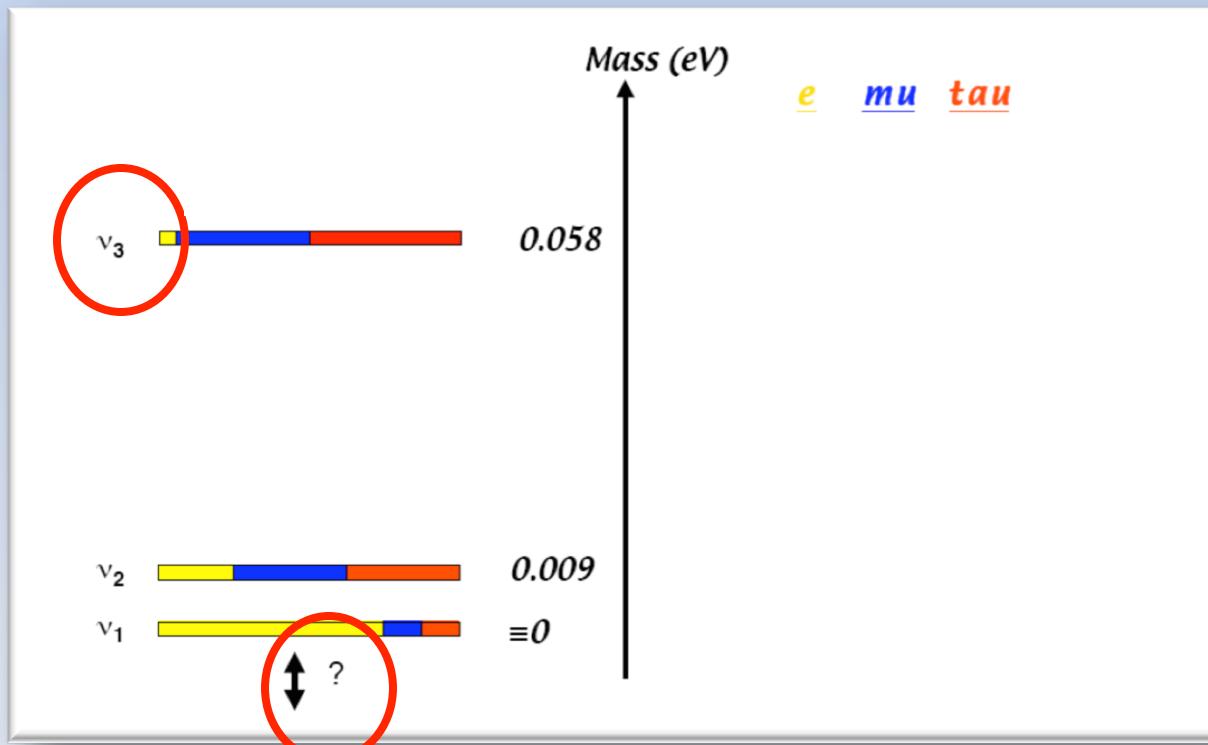
$$\nu_{l\text{L}}(x) = \sum_{j=1}^3 U_{lj} \nu_{j\text{L}}(x)$$

Disappearance Formula

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2 \left(\Delta m_{ee}^2 \cdot \frac{L}{E} \right) - \cos^4 \theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2 \left(\Delta m_{21}^2 \cdot \frac{L}{E} \right)$$

Neutrinos: Completing the Picture

- θ_{13} – the last mixing angle (reactor – now have it!!)
- Absolute mass scale (\rightarrow Tritium β endpoint, cosmology...)
- Mass hierarchy (\rightarrow accelerator, reactor?)
- CP violation – “leptogenesis” (\rightarrow accelerator)
- Antineutrino=neutrino (Majorana \rightarrow double β decay)?

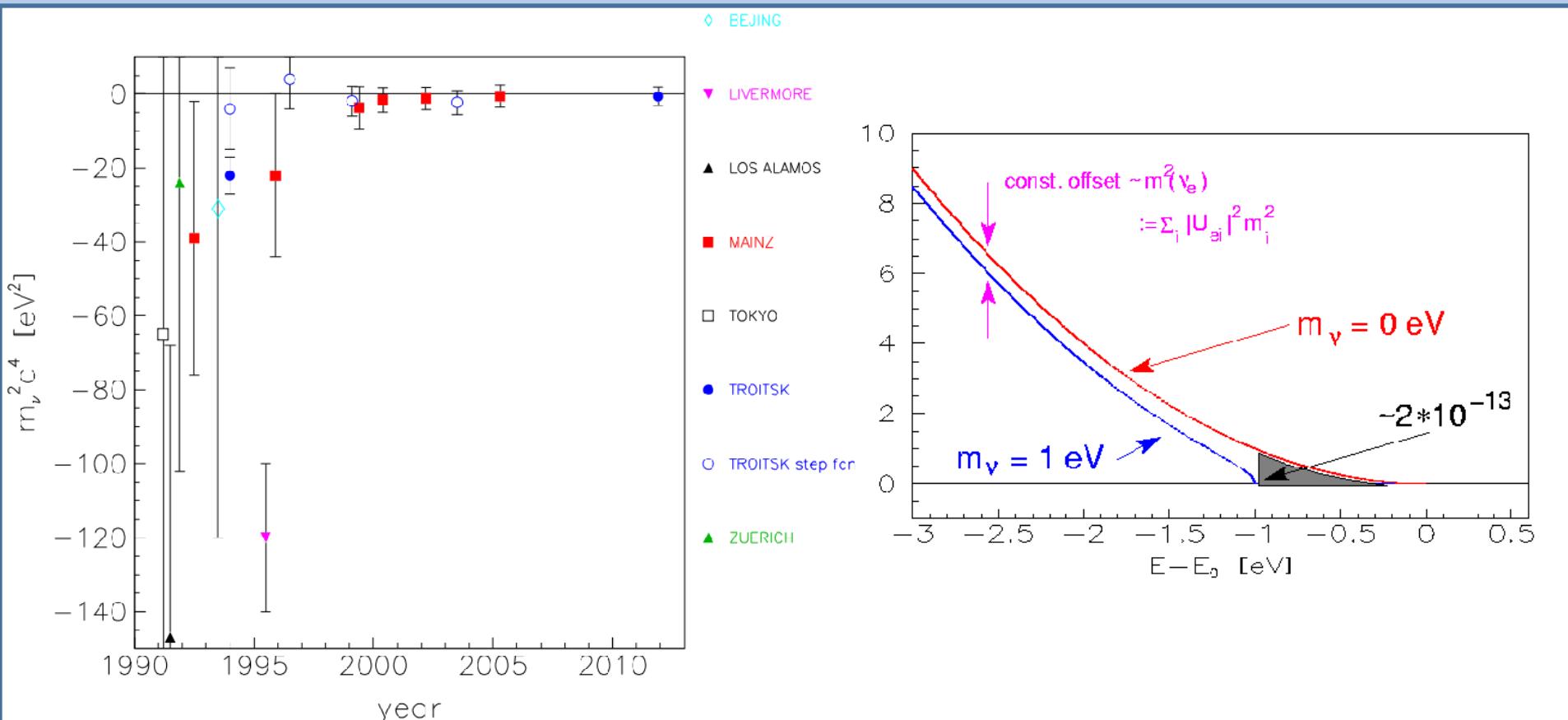


Global Fits

Parameter	Hierarchy	Best fit	1σ range
$\delta m^2/10^{-5} \text{ eV}^2$	NH or IH	7.37	7.21 – 7.54
$\sin^2 \theta_{12}/10^{-1}$	NH or IH	2.97	2.81 – 3.14
$\Delta m^2/10^{-3} \text{ eV}^2$	NH	2.50	2.46 – 2.54
$\Delta m^2/10^{-3} \text{ eV}^2$	IH	2.46	2.42 – 2.51
$\sin^2 \theta_{13}/10^{-2}$	NH	2.14	2.05 – 2.25
$\sin^2 \theta_{13}/10^{-2}$	IH	2.18	2.06 – 2.27
$\sin^2 \theta_{23}/10^{-1}$	NH	4.37	4.17 – 4.70
$\sin^2 \theta_{23}/10^{-1}$	IH	5.69	4.28 – 4.91 \oplus 5.18 – 5.97
δ/π	NH	1.35	1.13 – 1.64
δ/π	IH	1.32	1.07 – 1.67
$\Delta\chi^2_{\text{I-N}}$	IH–NH	+0.98	

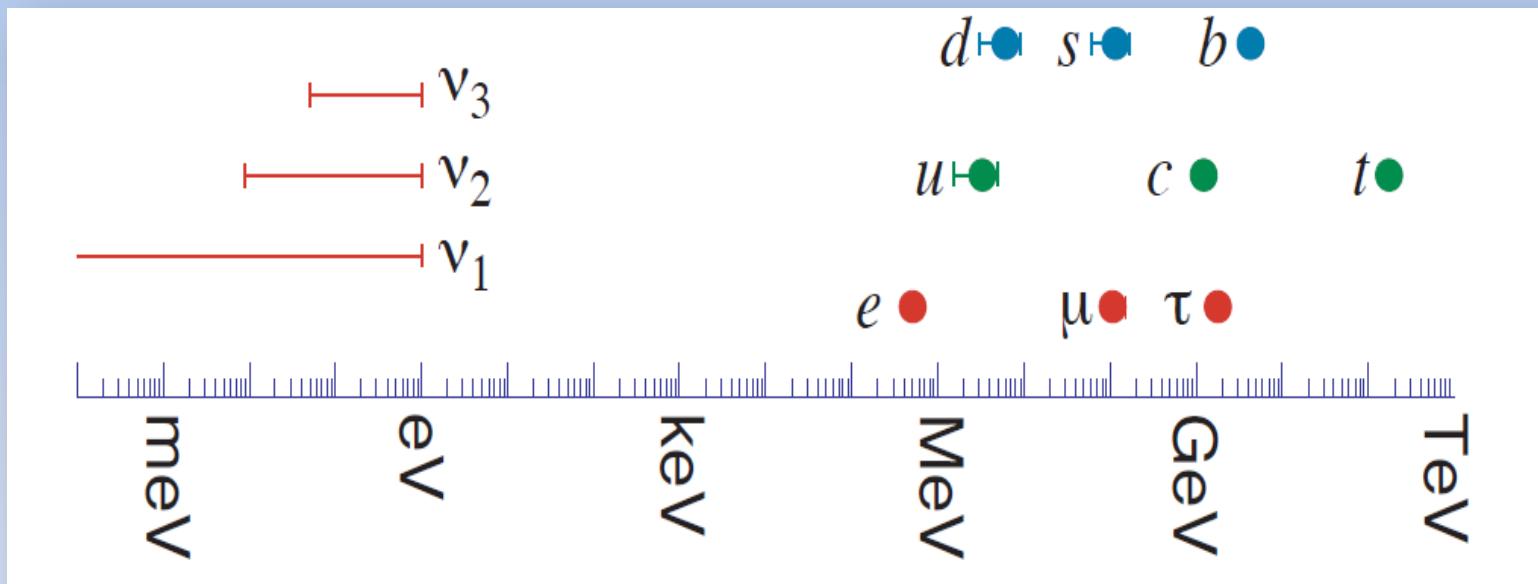
arXiv:1601.07777

Absolute Neutrino Mass Limits



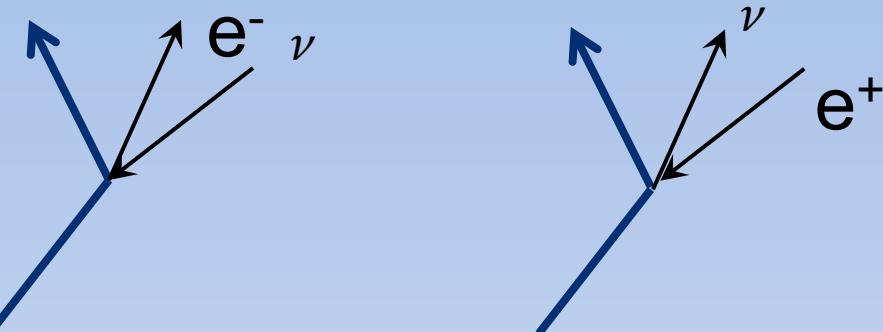
- Present limit from tritium decay: < 2 eV
- Cosmology: $\sum m_i < 0.23$ eV (95% CL)

Masses of Matter particles

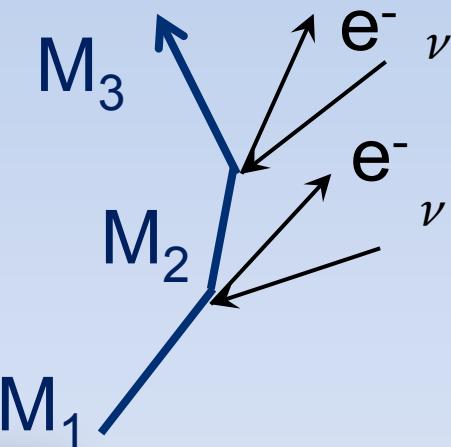


- Higgs mechanism not likely responsible for neutrino masses
- “See-saw” is most common alternative
 - Majorana neutrinos!
 - Leptogenesis

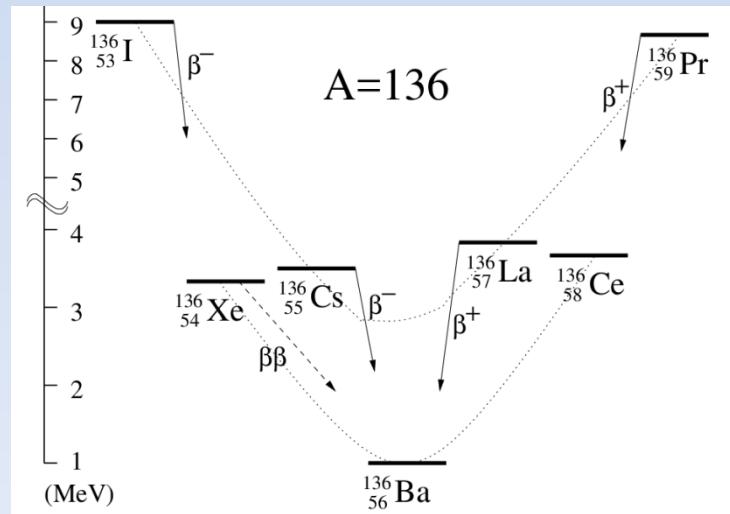
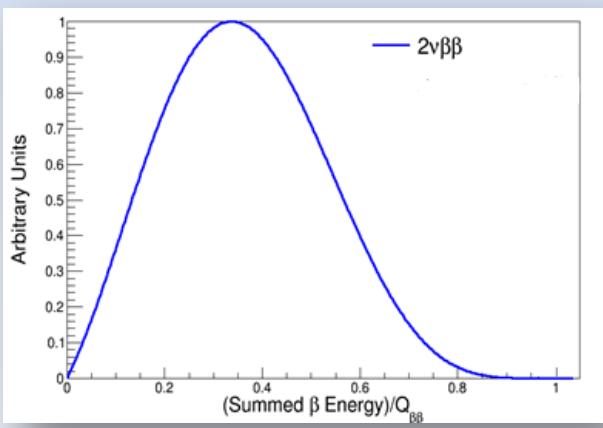
- β^\pm decay



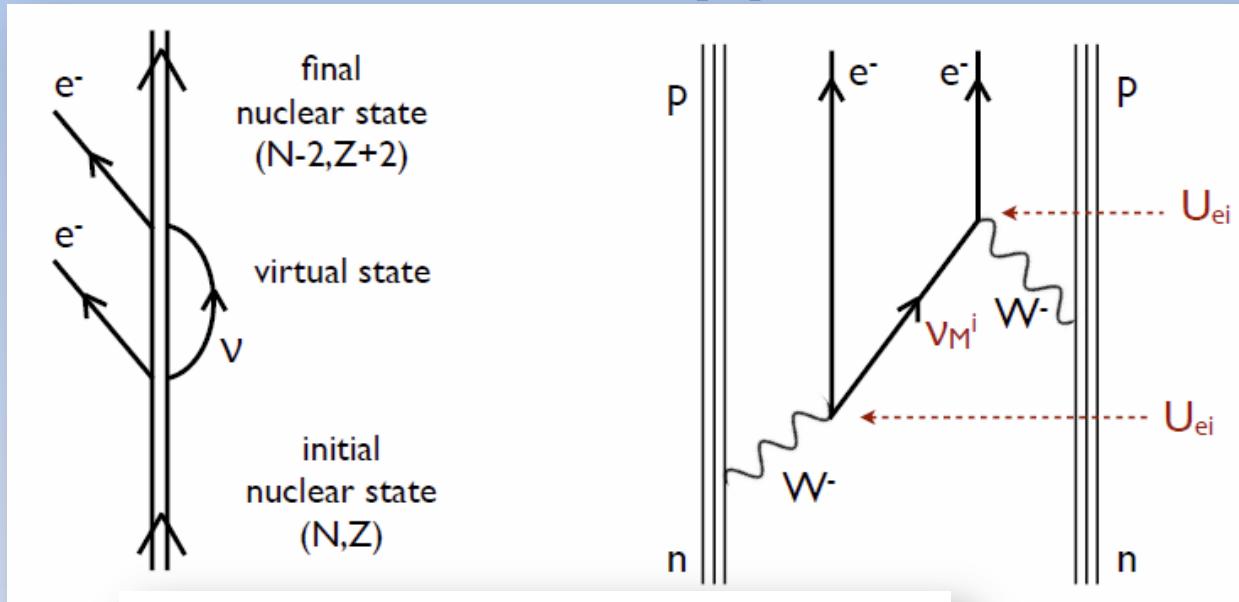
- $2\nu\beta\beta$ decay



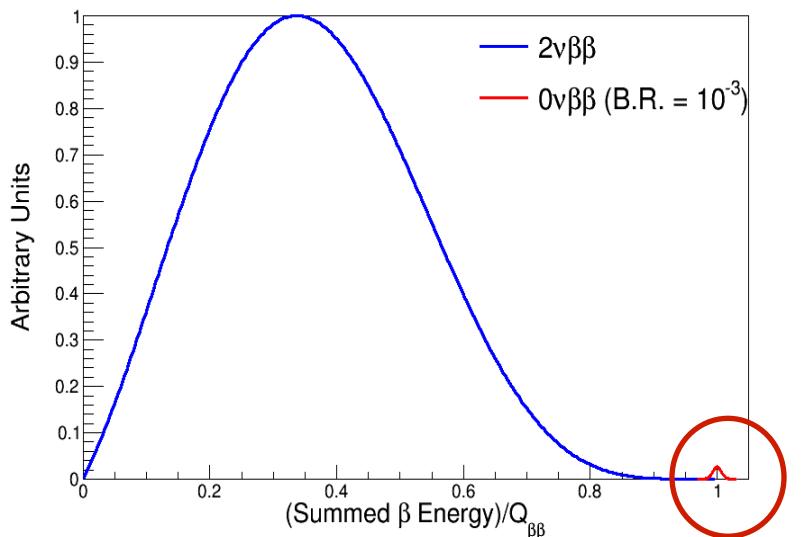
- $M_2 > M_1 > M_3$
- 2nd order weak process



$0\nu\beta\beta$ Decay



- $\Delta L=2 !!$
- Majorana ν
- Flip helicity:
 - RH coupling
 - $m \neq 0$

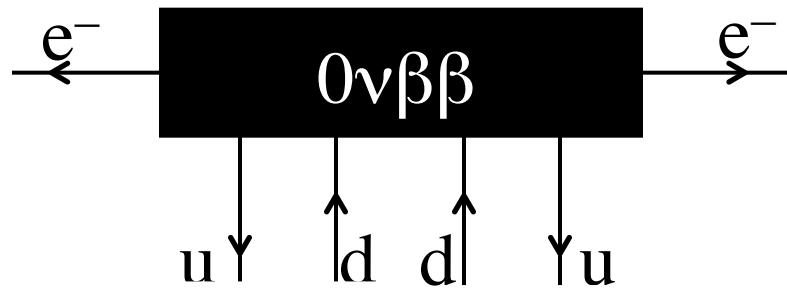


Experimental Issues

- Good energy resolution
- Low background

Neutrinoless $\beta\beta$ Decay

Whatever processes cause $0\nu\beta\beta$, its observation would imply the existence of **a Majorana mass term and thus would represent New Physics:** Schechter and Valle,82



By adding only Standard model interactions we obtain

$$(\bar{\nu} \nu)_R \rightarrow (\nu)_L \text{ **Majorana mass term**}$$

→ Observing the $0\nu\beta\beta$ decay implies that ν are massive Majorana particles.

NLDBD and Neutrino Mass

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space

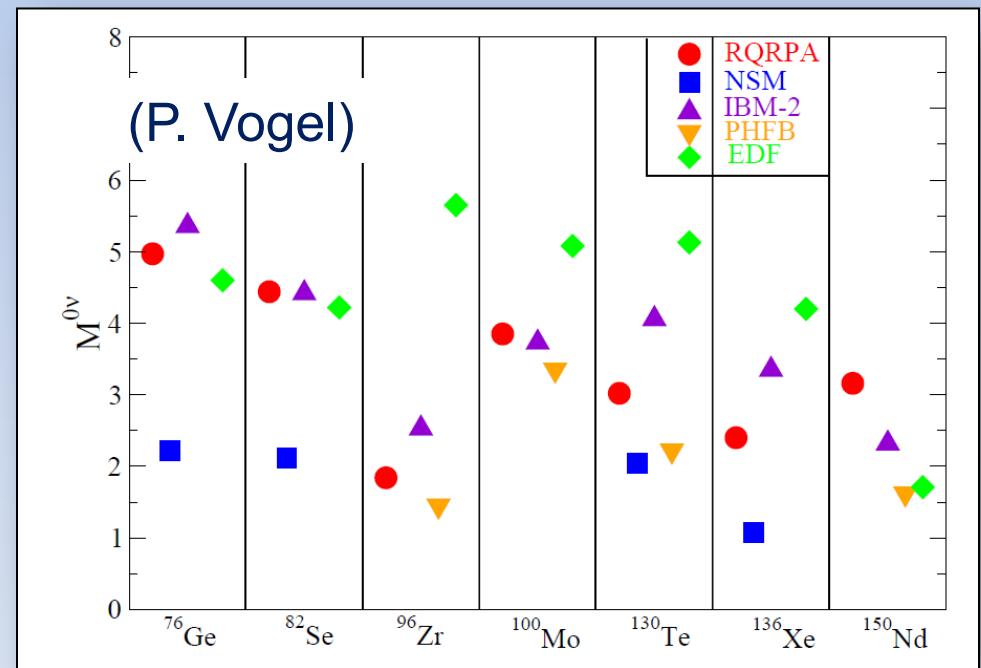
Nuclear Matrix Element

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$$

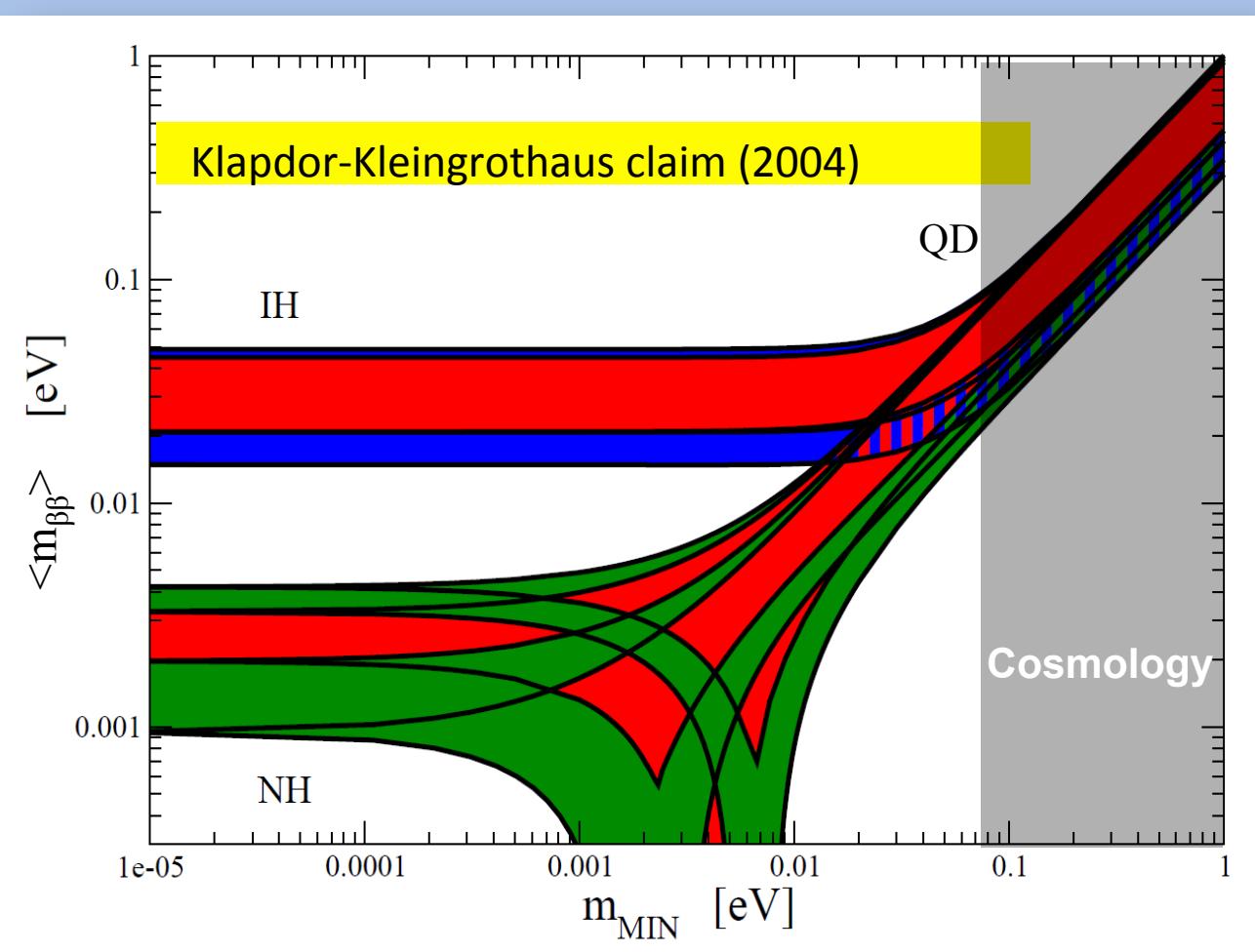
Nuclear Theory

- Variety of techniques used for nuclear matrix elements (QRPA, NSM, etc.) give a range of results

- What is the correct answer?



- There is additional uncertainty regarding possible quenching of g_A in nuclei (role of 2 body currents?)

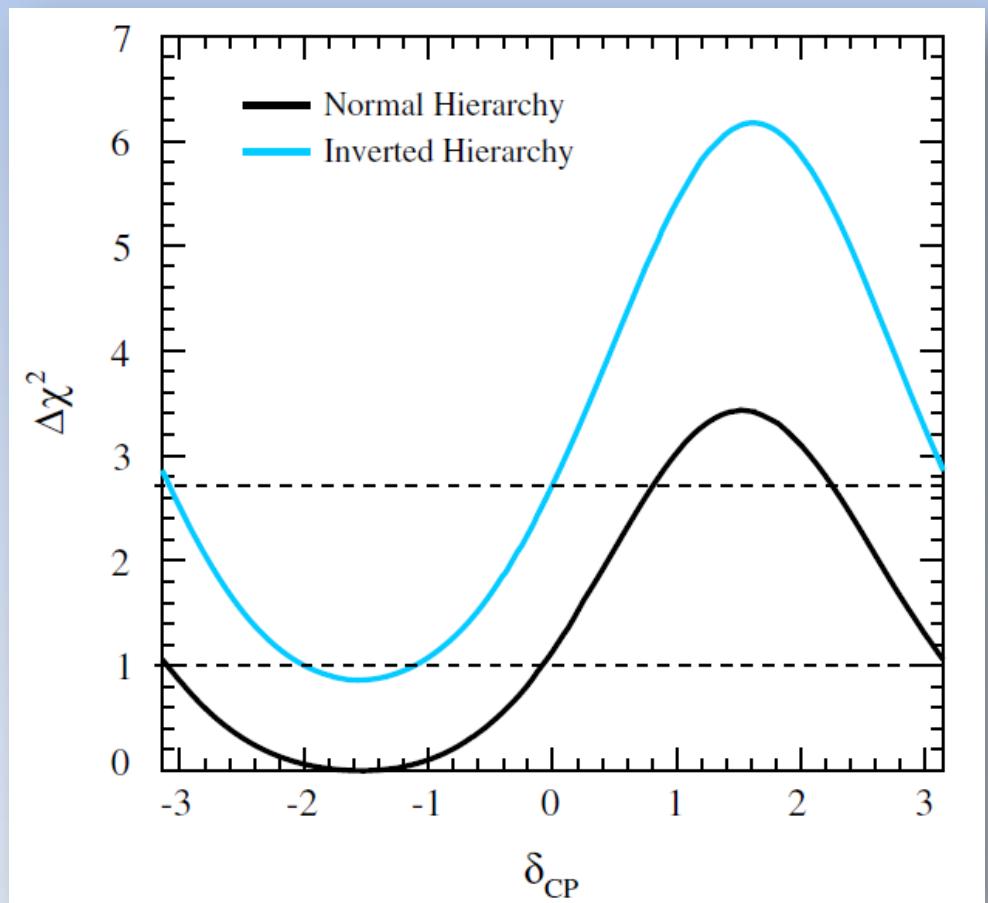


Note: colored bands
Indicate allowed
variation of U_{ei} due to
unknown Majorana
phases and uncertainty
in mixing angles

- $\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$
- $m_{\text{MIN}} = \text{lightest } m_{\nu i}$

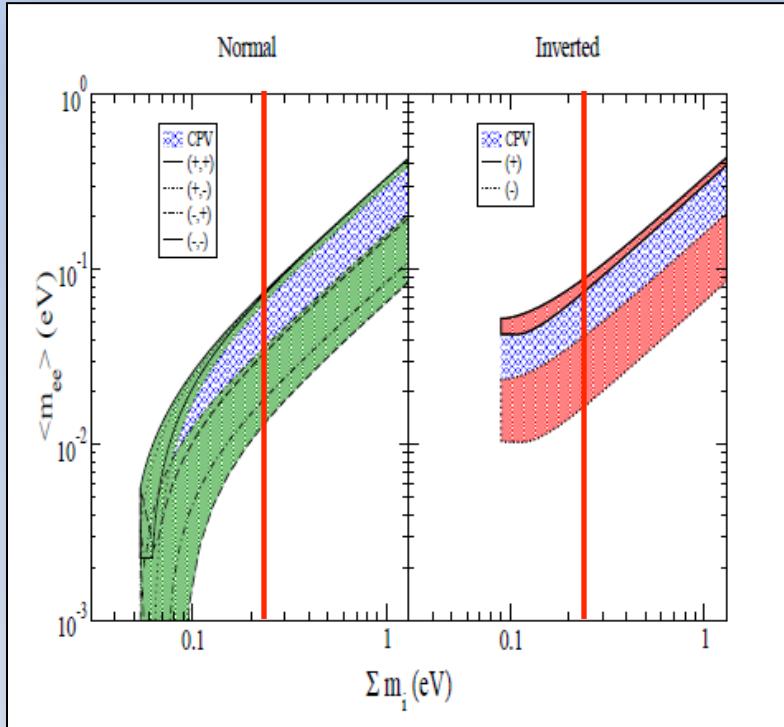
Neutrino Oscillation Experiments

- T2K reports the result shown (combined fit with reactor expts)
 - favors $\delta_{CP} \sim -\pi/2$
 - slightly favors NH
- First results from NovA at Fermilab are consistent
- Both keep running...
- PINGU, JUNO, RENO50 all aim for mass hierarchy within a decade



Phys.Rev. D91 (2015) 7, 072010

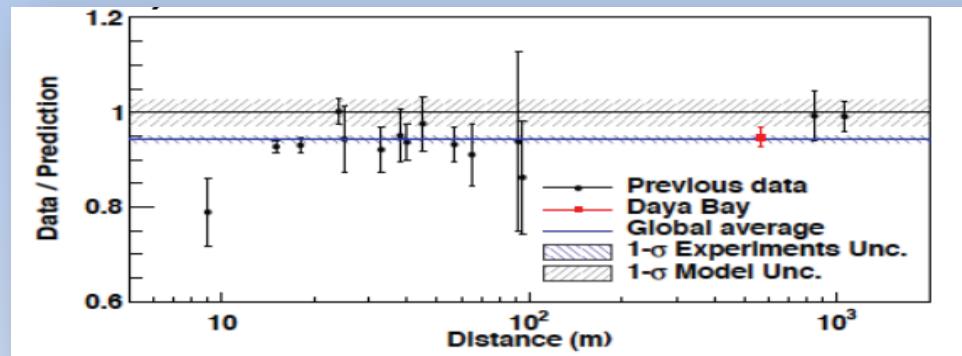
Cosmological Limits



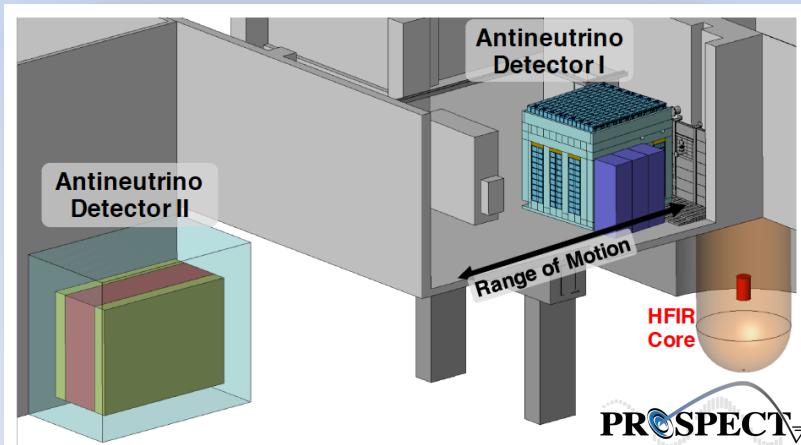
- Within the Λ CDM model, cosmology probes the neutrino freestreaming scale (neutrino hot dark matter component), which depends on $\Sigma \equiv \sum_i m_i$ and the relic neutrino energy spectra
- Current combined bound: $\Sigma < 230$ meV
- Projected bounds (~ 5 years): $\Sigma < 100$ meV (can tell ordering)
- Projected bounds (~ 10 years): $\Sigma < 50$ meV

Sterile Neutrinos

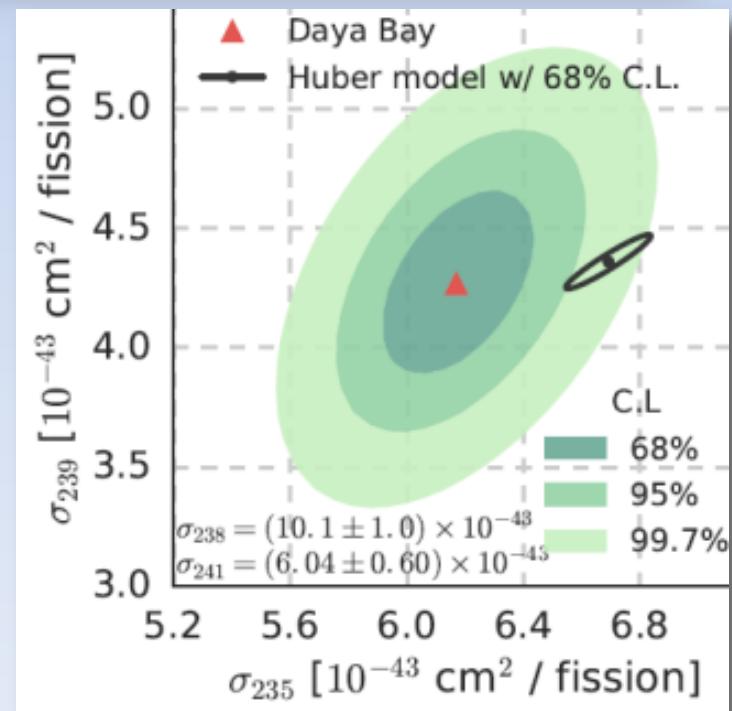
- Reactor Anomaly:



- Fits to sterile ν 's:

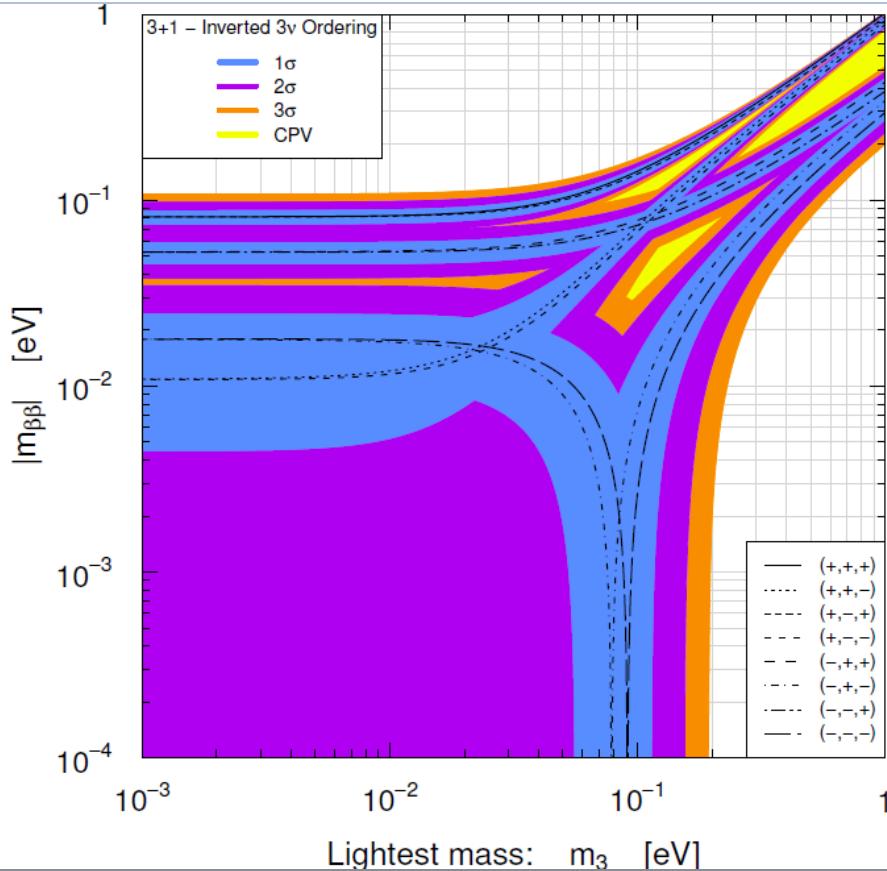
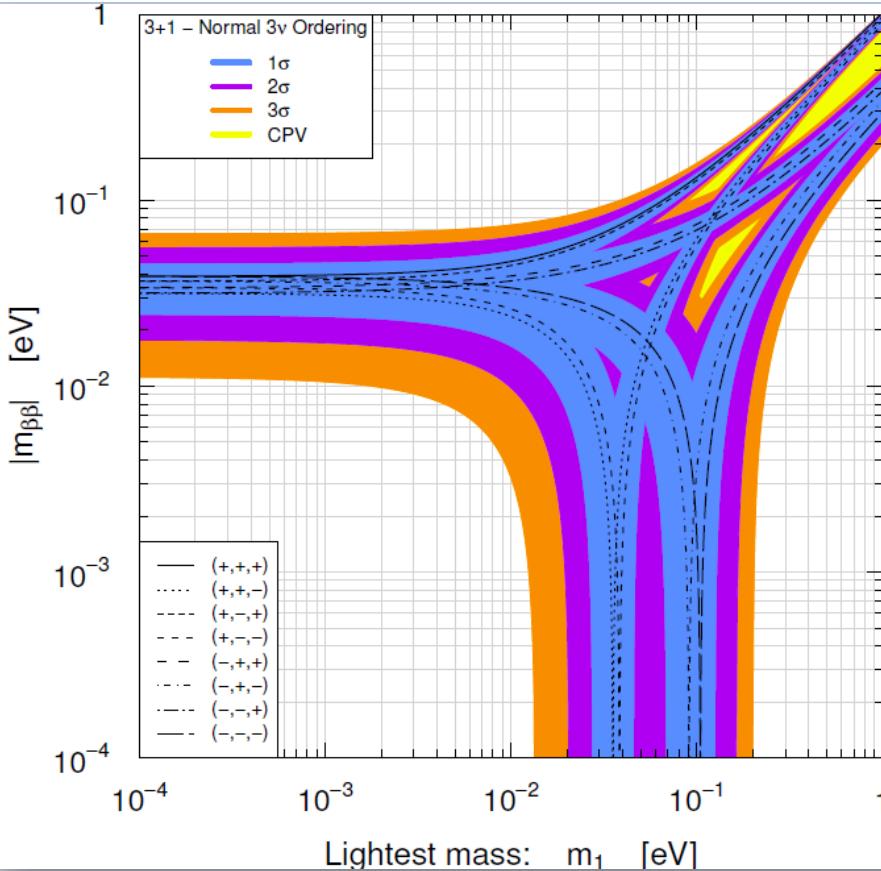


Many new experiments being mounted and proposed to confirm/refute interpretation



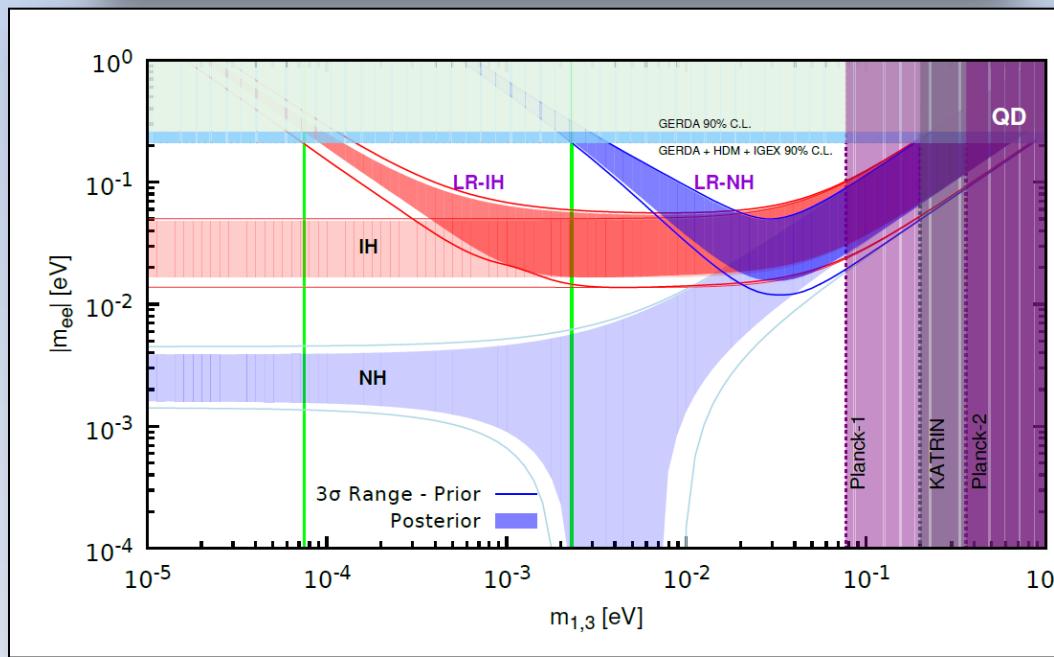
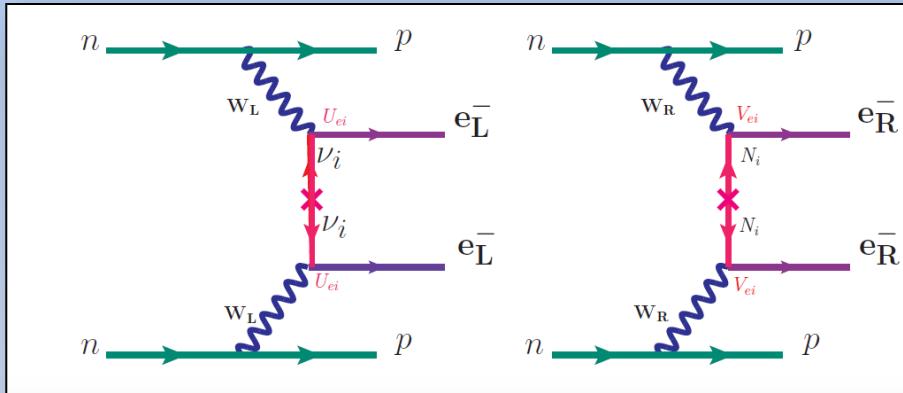
Sterile Neutrinos and NLDBD

$$|m_{\beta\beta}| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3 + |U_{e4}|^2 e^{i\alpha_4} m_4 \right|$$



arXiv:1507.08204

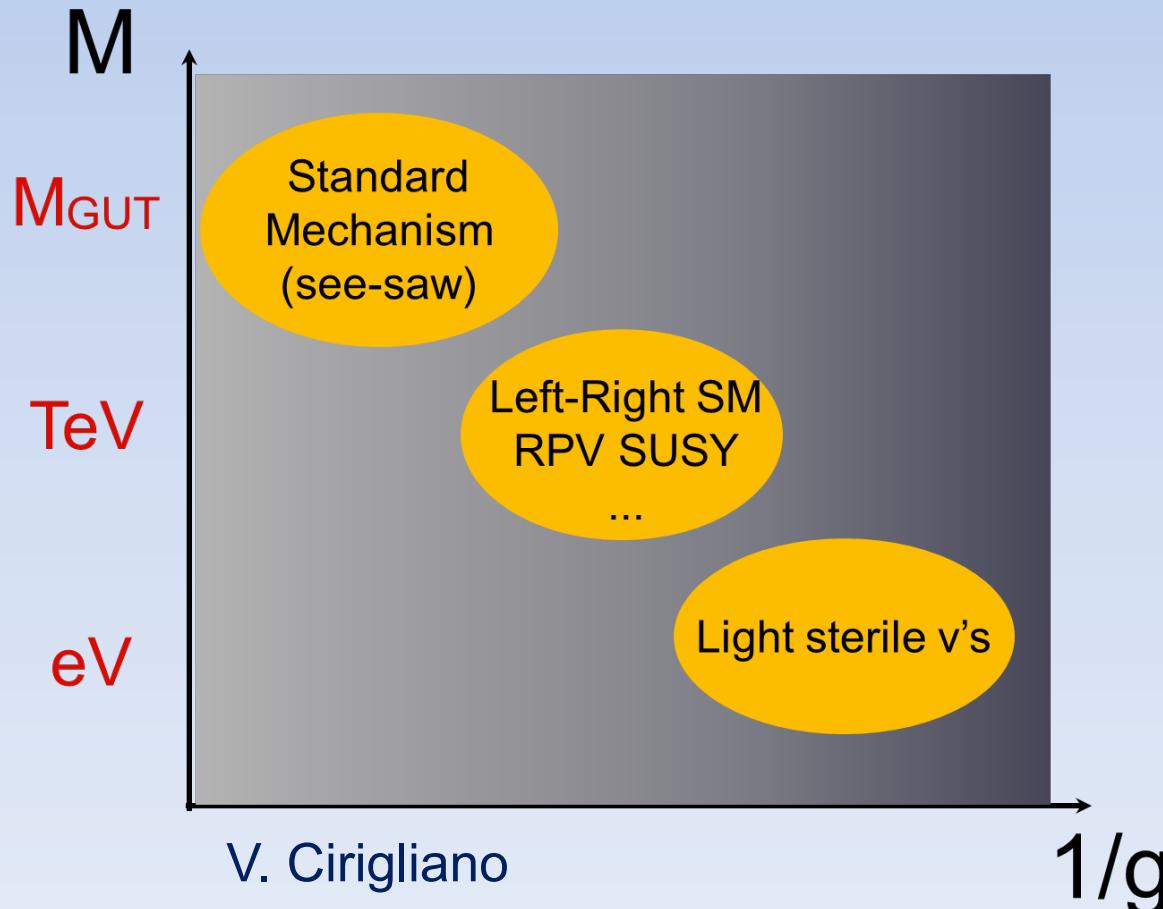
New Physics and LHC



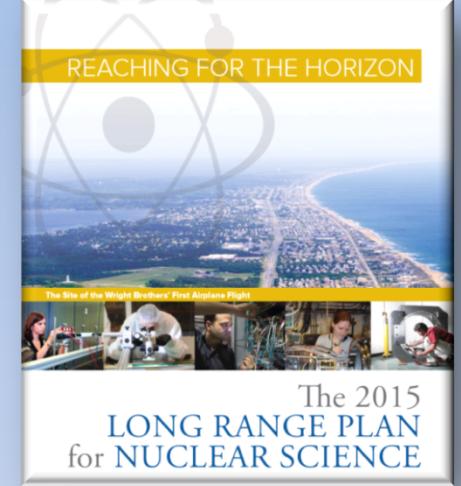
arXiv:1508.07286

Lepton Number Violation and $0\nu\beta\beta$

- Ton-scale $0\nu\beta\beta$ probes LNV from a variety of mechanisms and scales of masses (M) and couplings (g)



NSAC 2015 Long Range Plan



RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

Initiative for Detector and Accelerator Research and Development:

We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC.

Methods

- ^{136}Xe TPCs (liquid, gas)
- ^{76}Ge Crystals
- TeO_2 bolometers (\rightarrow enhancements)
- Doped Liquid Scintillators (^{136}Xe , Te)
- Foils with tracking chambers (^{82}Se +)

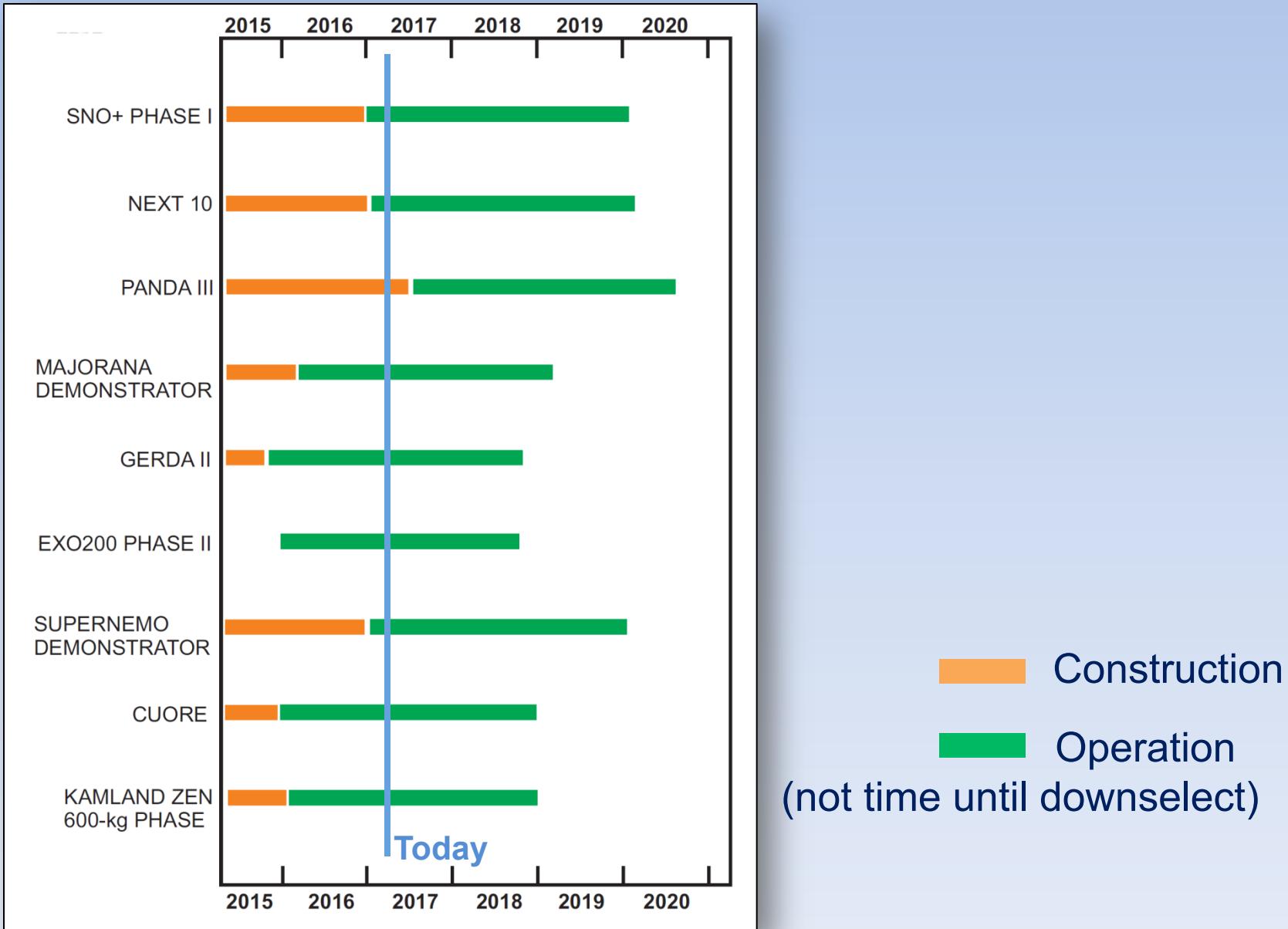
Current Projects

Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved (10^{26} yr)
CUORE	^{130}Te	206	>0.028
MAJORANA	^{76}Ge	24.7	
GERDA	^{76}Ge	18-20	>0.53
EXO200	^{136}Xe	79	>0.11
NEXT-100	^{136}Xe	100	
SuperNEMO	$^{82}\text{Se+}$	7	>0.001
KamLAND-Zen	^{136}Xe	434	>1.07
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

Primary goals:

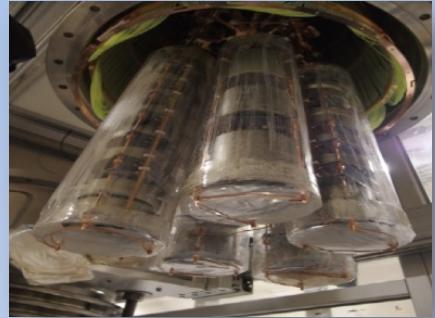
- Demonstrate background reduction for next generation experiment
- Extend sensitivity to $T_{1/2} \sim 10^{26}$ years.

Updated Timeline (2015)

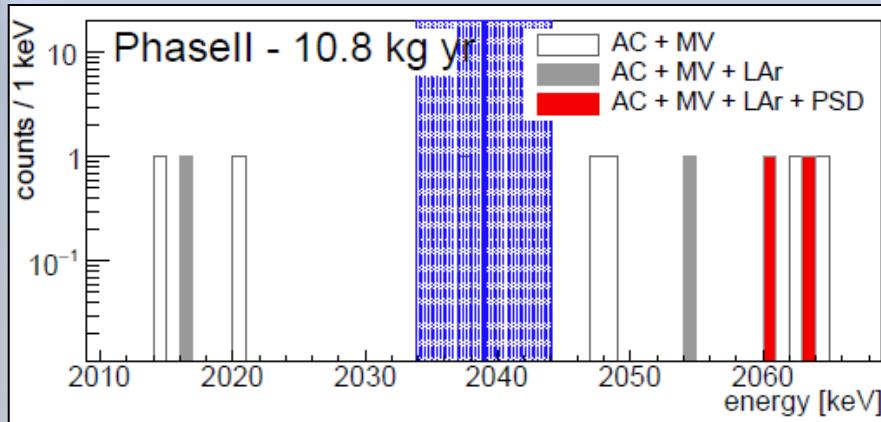




GERDA Phase II (2016)



- 87% enriched ^{76}Ge detectors (crystals) in LAr
- $Q_{\beta\beta}=2039 \text{ keV}$
- Deployed in Dec 2015
 - 30 enriched BEGe (20 kg)
 - 7 enriched Coax (15.8 kg)
 - 3 natural Coax (7.6 kg)
- Single-site, multi-site pulse shape discrimination
- Active LAr veto shield

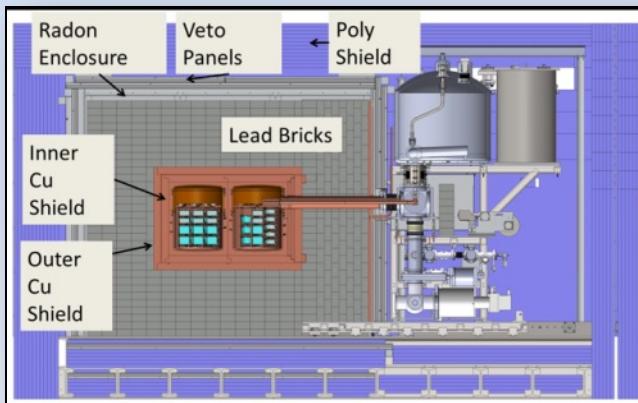
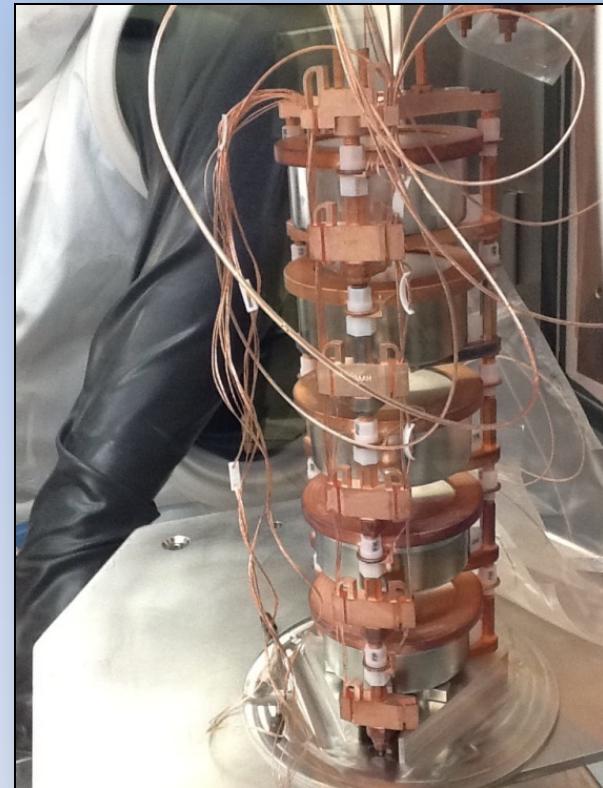


- 10.8 kg-year exposure
- $\sim 3 \text{ cts/ton/yr}$ for BEGe
- $T_{1/2} > 5.3 \times 10^{25} \text{ y}$
(90% CL, Phase I+II)

arXiv:1703.00570

Majorana Demonstrator

- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the region of interest (4 keV at 2039 keV)
 - 3 counts/ROI/t/y (after analysis cuts)
Assay U.L. currently ≤ 3.5
 - Scales to 1 count/ROI/t/y for a tonne experiment
- 44.8-kg of Ge detectors
 - 29.7 kg of 88% enriched ^{76}Ge crystals
 - 15.1 kg of natGe
 - Detector Technology: P-type, point-contact.



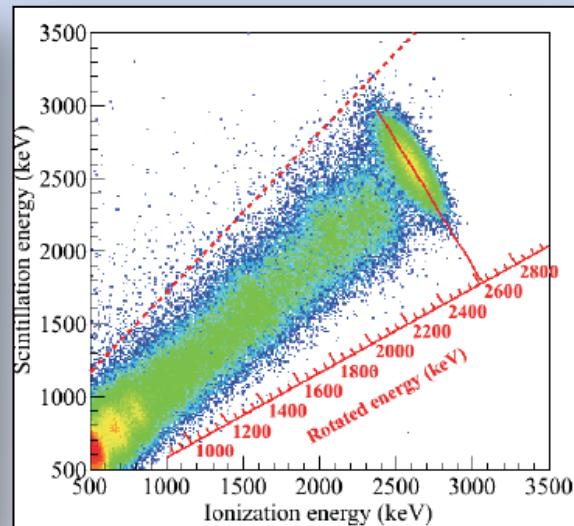
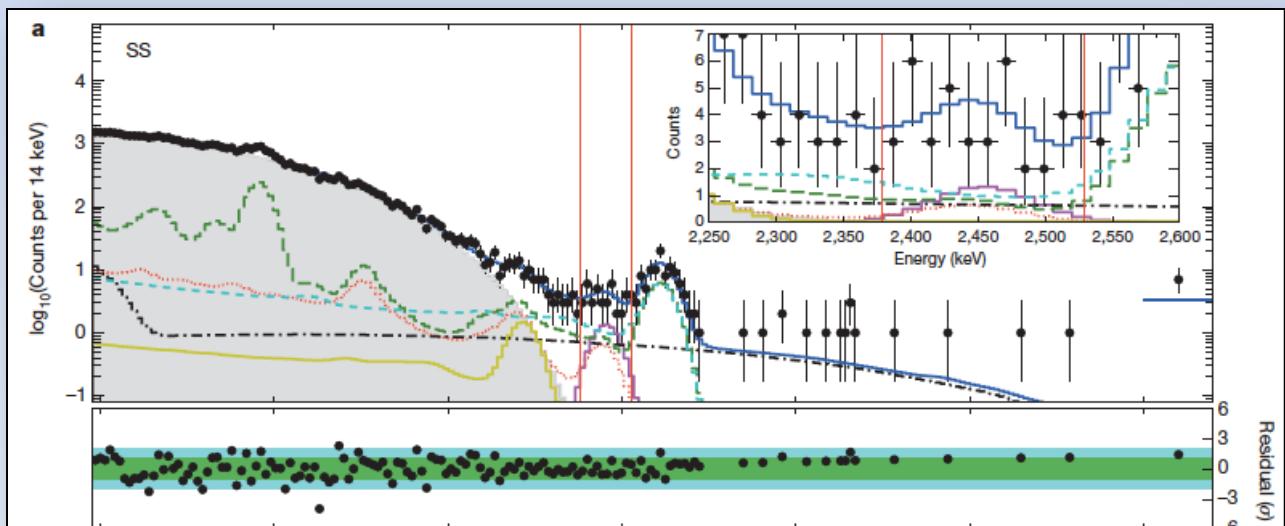
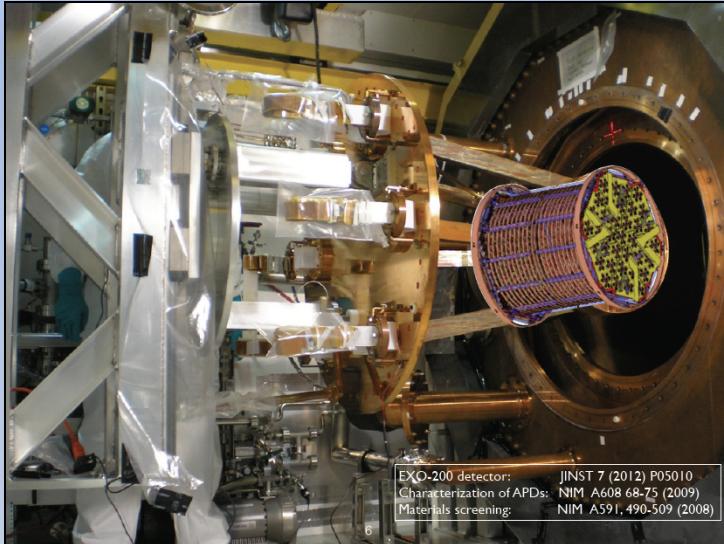
23^{+13}_{-10} counts/(ROI t y)

Elliott – Neutrino16

EXO-200 ^{136}Xe (2014)

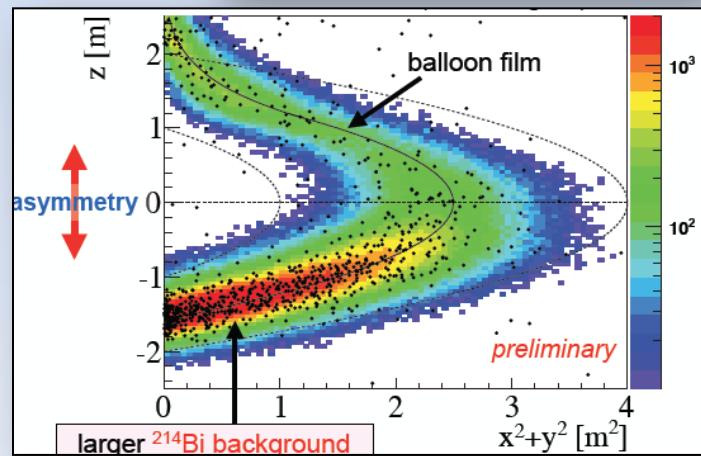
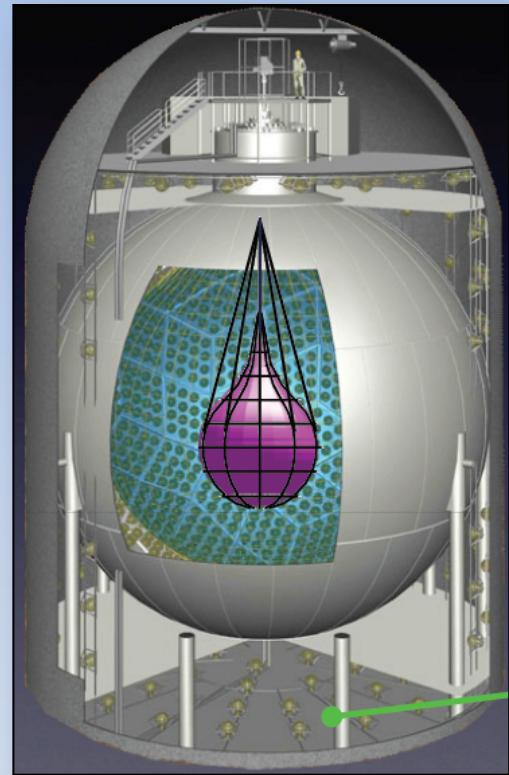
Enriched Liquid Xe in TPC

- $Q_{\beta\beta} = 2457.8 \text{ keV}$
 - 200 kg of 80.6 % enriched ^{136}Xe
 - 75.6 kg fiducial mass,
 - 100 kg years exposure
 - Combine Scintillation-Ionization signal for improved resolution (88 keV FWHM @ $Q_{\beta\beta}$)
 - Single site - Multisite discrimination
- $T_{1/2} > 1.1 \times 10^{25} \text{ y (90\% CL)}$



KamLAND-ZEN ^{136}Xe (2016)

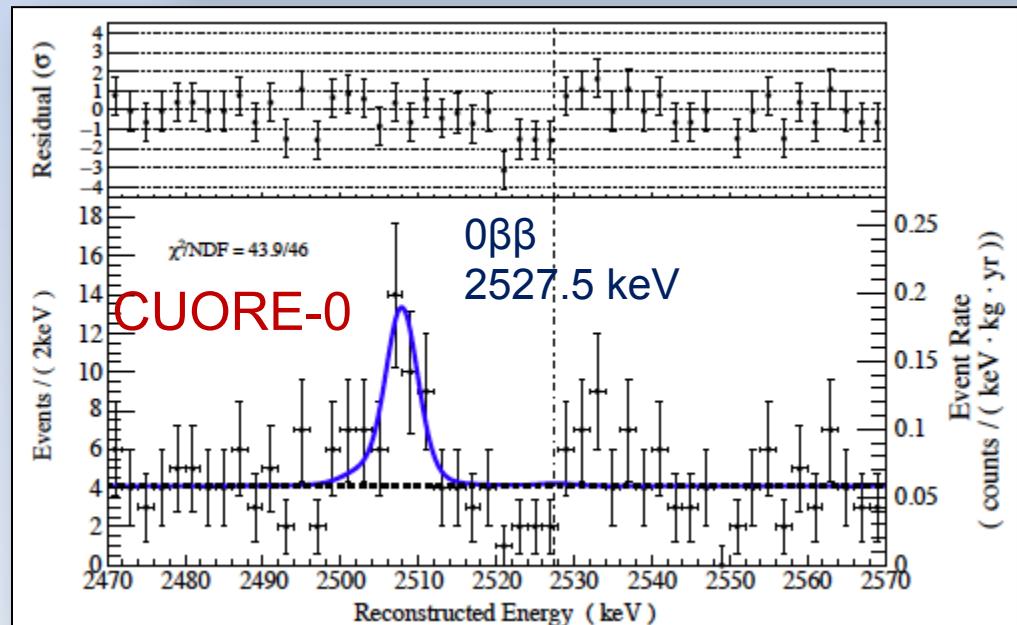
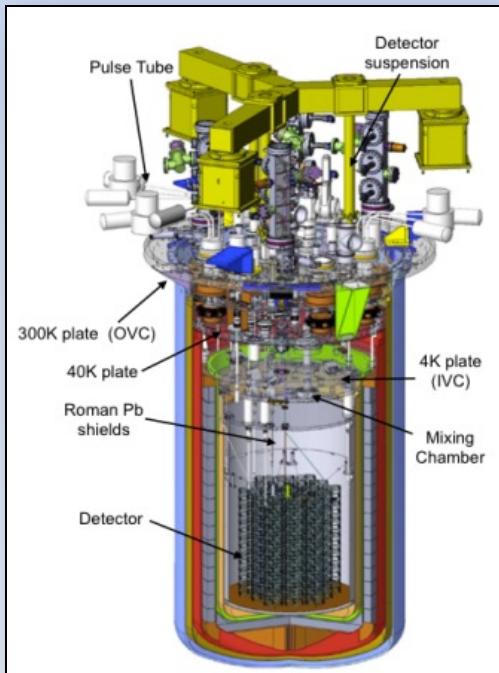
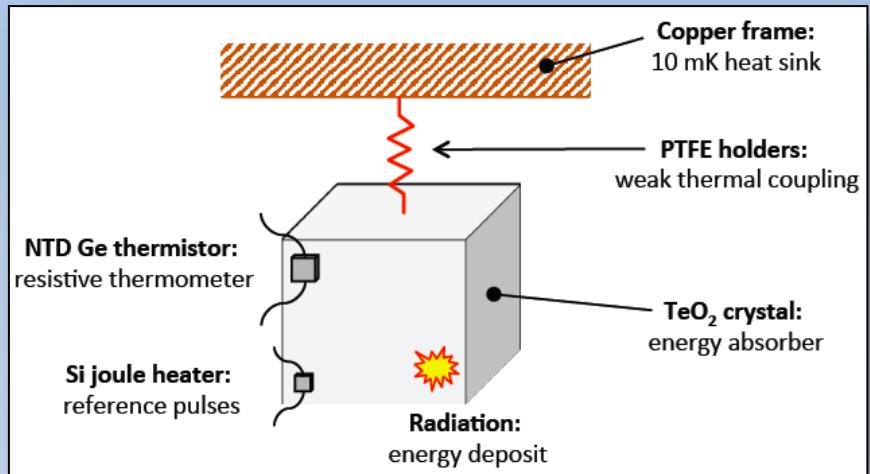
- ^{enr}Xe in liquid scintillator, balloon of $R=1.5$ m
- $Q_{\beta\beta}=2457.8$ keV
- Phase 1
 - 179 kg (2.44% by Xe wt.) 91.7% enriched ^{136}Xe
 - $R=1.35$ m fiducial cut
 - 213.4 days, with 89.5 kg years exposure
 - 400 keV FWHM @ $Q_{\beta\beta}$
 - evidence for ^{110m}Ag contamination
 $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)
- Phase 2
 - 383 kg (2.96% by Xe wt.)
 - $R=1$ m fiducial cut
 - 504 kg years exposure
 - ^{110m}Ag contamination reduced by x10
 $T_{1/2} > 9.2 \times 10^{25}$ y (90% CL)
 - Combined (1&2) $T_{1/2} > 1.07 \times 10^{26}$ y (90% CL)
- Phase 3 – 750kg ^{enr}Xe (2017)



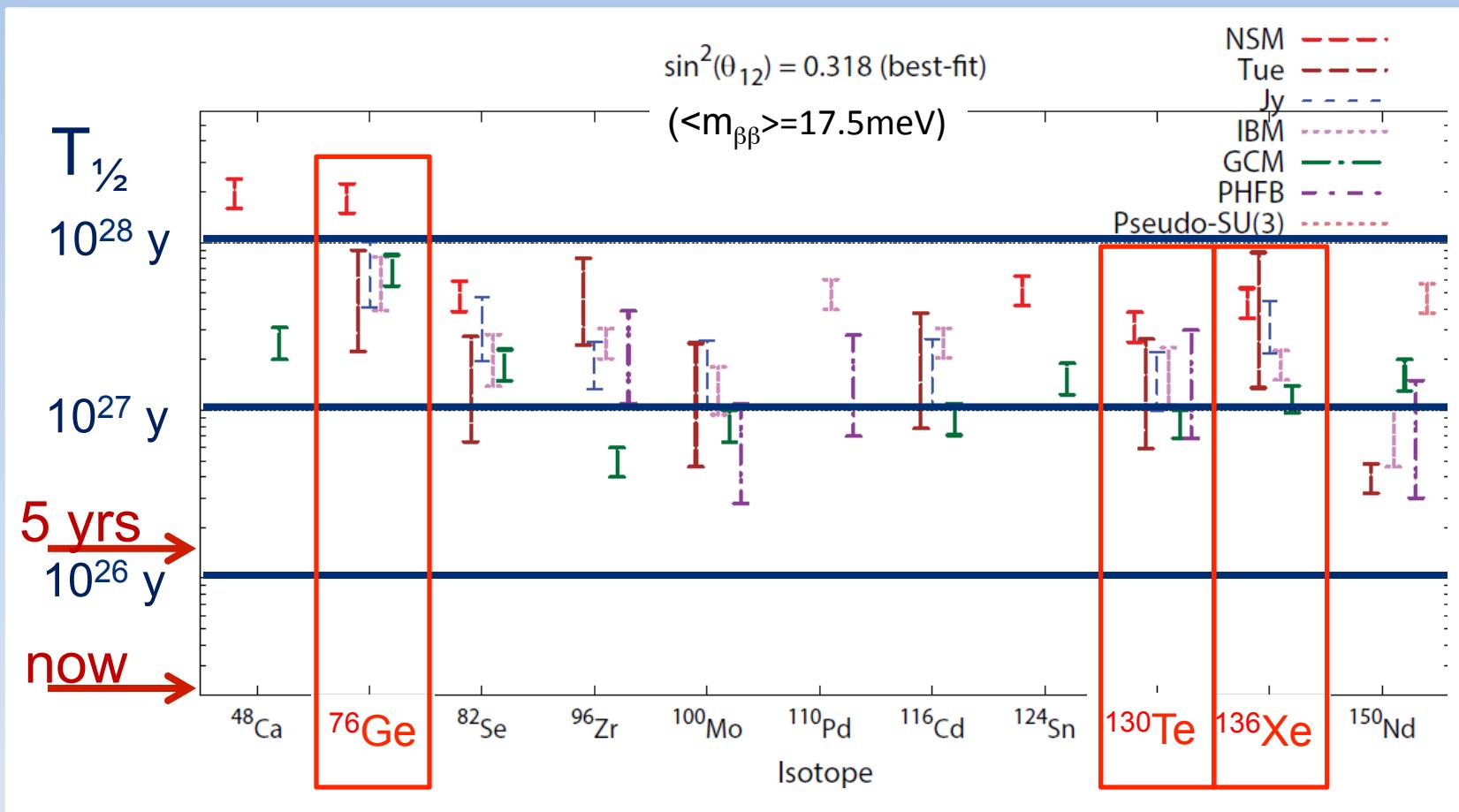
KamLAND ZEN Collaboration, Shirai, Neutrino 2016

CUORE ^{130}Te (2016)

- Located at LNGS (Italy), ~3600 m.w.e. shield
- Array of 988 natTeO₂ thermal detectors, arranged in 19 towers, 13 floors each. A total mass of 206 kg of ^{130}Te
- Operated at 10 mK
- Fully installed in 2016



Inverted Hierarchy Coverage



$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Figure source: A. Dueck, W. Rodejohann, and K. Zuber, Phys. Rev. D83 (2011) 113010.

Major Issue: Background

- For “background-free” experiment, lifetime sensitivity goes as $T_{1/2} \sim M \cdot t_{\text{run}}$ (M = isotope mass)
 - factor of 50 in $T_{1/2}$ needs factor of 50 in M (for constant t_{run})
 - For experiment with background, as $T_{1/2} \sim (M \cdot t_{\text{run}})^{1/2}$
 - factor of 50 in $T_{1/2}$ needs factor of 2500 in M (for constant t_{run})
 - Background reduction is the key to a successful program
 - deep underground
 - radiopurity
 - better E resolution
 - better event characterization
- R&D will be crucial

Simple Background Estimate

NLDBD Rate = $N \times \ln(2) / T_{1/2}$ (assume $T_{1/2} \approx 10^{28}$ yr)

For 1 Tonne, $N=10^6 g \times 6 \times 10^{23} / MW$
(MW= 67, 130, 136 → use MW≈100)

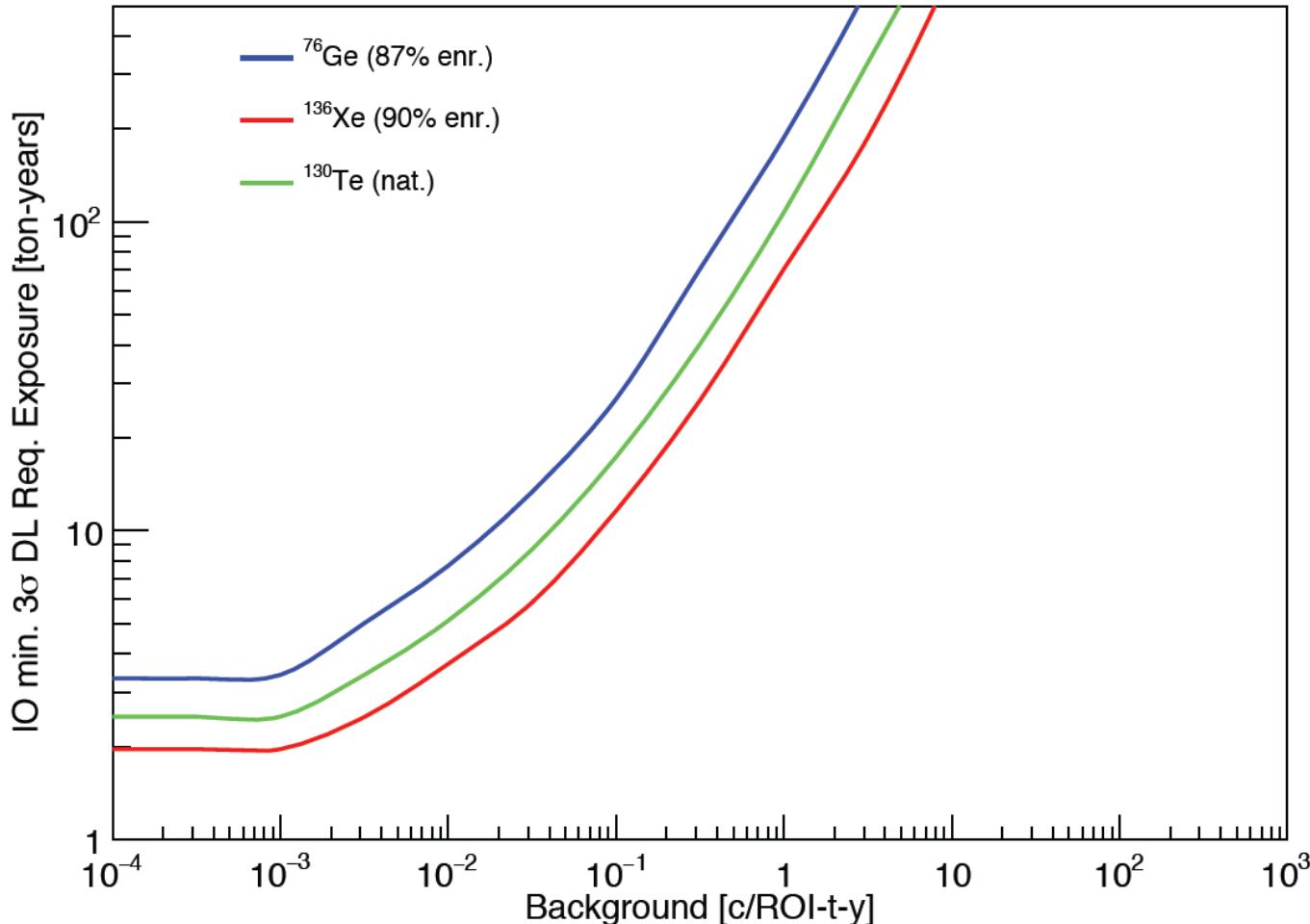
So $N \approx 6 \times 10^{27}$

NLDBD Rate = 0.4 /Tonne/yr

Background free → Background < 0.1/Tonne/yr/ROI

Required 3σ Exposure vs. Background

J. Detwiler



"Required" exposure assuming minimum IO $m_{\beta\beta}=18.3$ meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Potential Contributions to the Background

- Primordial, natural radioactivity in the detector and array components: U, Th, K
- Backgrounds from cosmogenic activation while material is above ground ($\beta\beta$ -isotope or shield specific, ^{60}Co , ^3H ...)
- Backgrounds from the surrounding environment:
 - external γ , (α,n) , (n,α) , Rn plate-out, etc.
- μ -induced backgrounds generated at depth:
 - $\text{Cu}, \text{Pb}(n, n' \gamma)$, $\beta\beta$ -decay specific(n,n),(n,γ), direct μ
- 2 neutrino double beta decay (irreducible, E resolution dependent)
- Neutrino backgrounds (negligible)

Background Reduction Strategies

- Directly reduce intrinsic, extrinsic, & cosmogenic activities
 - Select and use ultra-pure materials
 - Minimize all non “source” materials
 - Clean (low-activity) shielding
 - Fabricate ultra-clean materials (underground fab in some cases)
 - Go deep — reduced μ 's & related induced activities
- Utilize background measurement & discrimination techniques

$0\nu\beta\beta$ is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions

 - Energy resolution
 - Active veto detector
 - Tracking (topology)
 - Particle ID, angular, spatial, & time correlations
 - Fiducial Fits
 - Granularity [multiple detectors]
 - Pulse shape discrimination (PSD)
 - Ion Identification

Guidelines for the Future

The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments:

- 1) Discovery potential: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}=15$ meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.
- 2) Staging: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.
- 3) Standard of proof: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.

Guidelines for the Future (cont'd)

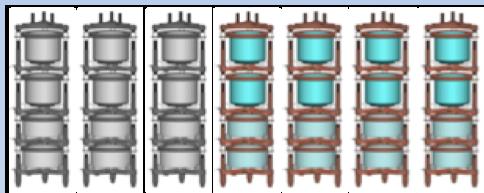
- 4) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.
- 5) International Collaboration: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.
- 6) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

Next Generation Tonne Scale Experiments

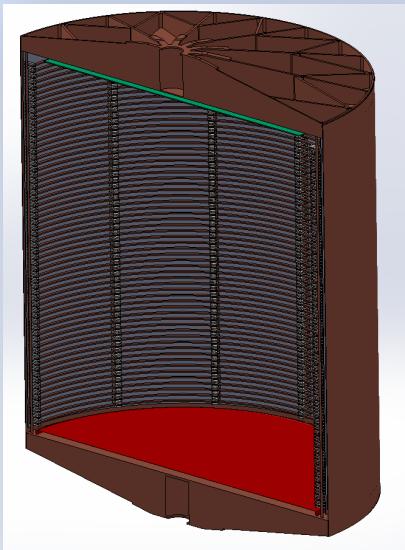
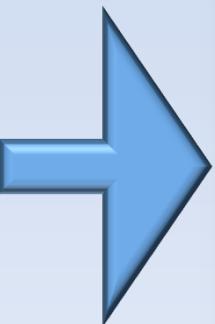
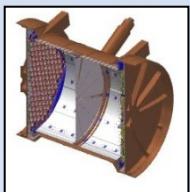
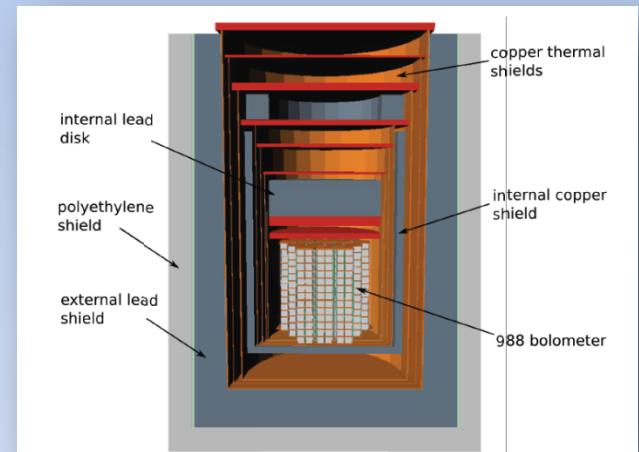
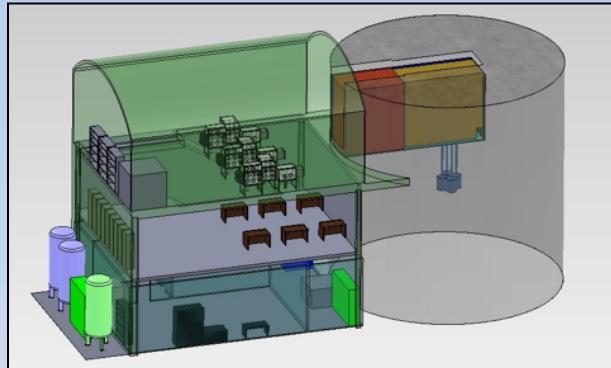
- Active international collaborations building on current efforts.
 - ^{76}Ge : Large Scale Ge, O(tonne) HPGE crystals (GERDA & MAJORANA)
 - ^{82}Se : SuperNEMO : Se foils, tracking and calorimeter, 100 kg scale
 - ^{136}Xe : nEXO — Liquid TPC, 5 tonnes
 - NEXT — High pressure gas TPC, tonne scale
 - KamLAND2 Zen — ^{136}Xe in scintillator, 0.75 tonnes
 - ^{130}Te : CUPID — Bolometer – Scintillation/Cerenkov
 - SNO+ Phase II — ^{130}Te in scintillator
 - Additional efforts underway in Asia (AMoRE, CANDLES, PandaX III, CDEX 1T) & Europe (LUCIFER, COBRA)
- Experiments can be done in a staged (phased) approach; many are considering stepwise increments
- Isotope enrichment (^{76}Ge , ^{82}Se , ^{136}Xe) requires time and \$s.
 - There is considerable dependence on Russia, and concern about the future availability of this source.
- Potential underground lab sites
 - SNOLAB, JingPing, Gran Sasso, SURF, CanFranc, Frejus, Kamioka, ANDES, Y2L

Next Generation Approaches

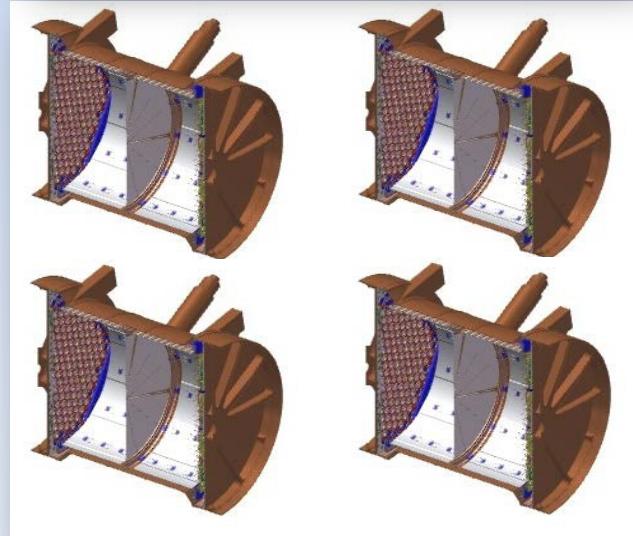
The issue is to scale up to ≥ 1 Tonne with low background.



$\times \sim 100 \rightarrow$



OR



Proposed U.S. R&D

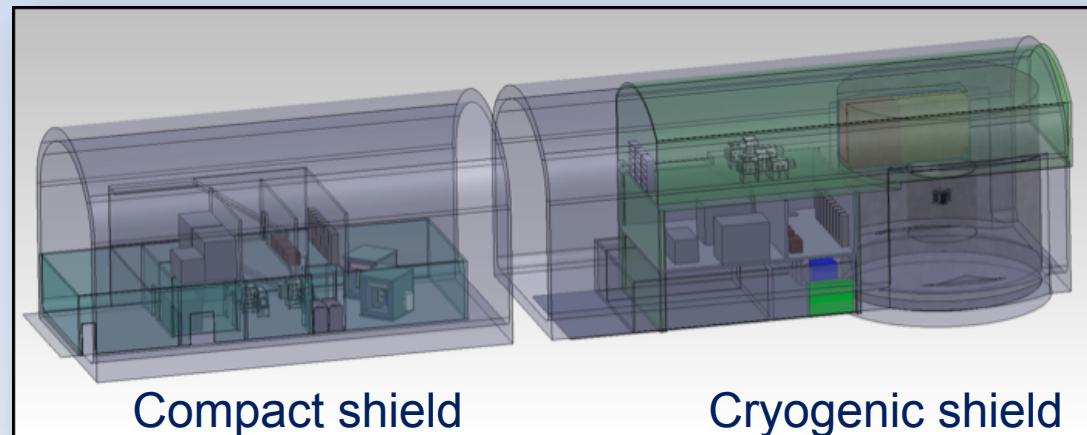
Germanium	Higher radiopurity connectors	Radiopure fabrication methods	
CUPID	Particle ID	Component radiopurity	Study Cosmogenics with CUORE
NEXT	Study NEXT10, DEMO, DEMO+	Fluorescence Ba detection	
PANDA X III	HV cage and radiopure pressure vessel	Topmetal readout	
SNO+ Phase II	Run SNO+	Load Te to 3%	Increase Light yield
nEXO	HV @ >50kV	Hi QE radiopure photodetectors (SiPM)	Electronics
SuperNEMO	Foil radiopurity	Scintillator/PMT improvement	Tracker improvement

Total estimated resources ~\$11M

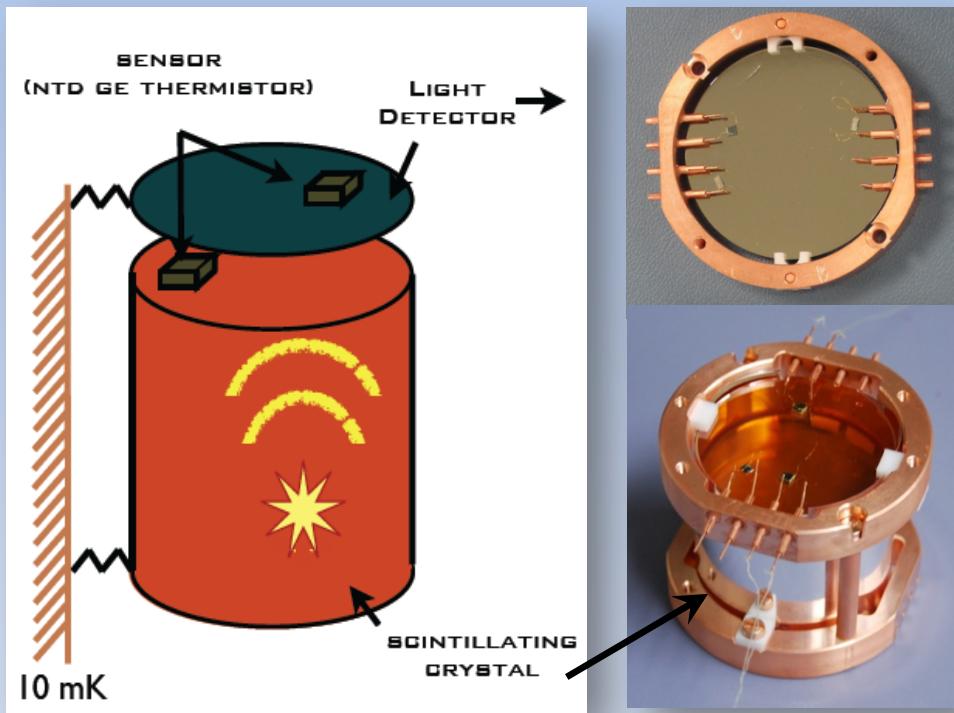
Large Scale ^{76}Ge

MAJORANA and GERDA are working towards the establishment of a single international ^{76}Ge $0\nu\beta\beta$ collaboration. (Name: LEGEND)

- Envision a phased, stepwise implementation;
 - e.g. $250 \rightarrow 500 \rightarrow 1000 \text{ kg}$ (1st phase combines current GERDA and MJD)
 - 5 yr 90% CL sensitivity: $T_{1/2} > 3.2 \cdot 10^{27} \text{ yr}$
 - 10 yr 3 σ discovery: $T_{1/2} \sim 3 \cdot 10^{27} \text{ yr}$
- Moving forward predicated on demonstration of projected backgrounds by MJD and/or GERDA
- Anticipate down-select of best technologies, based on results of the two experiments



Scintillating Bolometers



L. Cardani

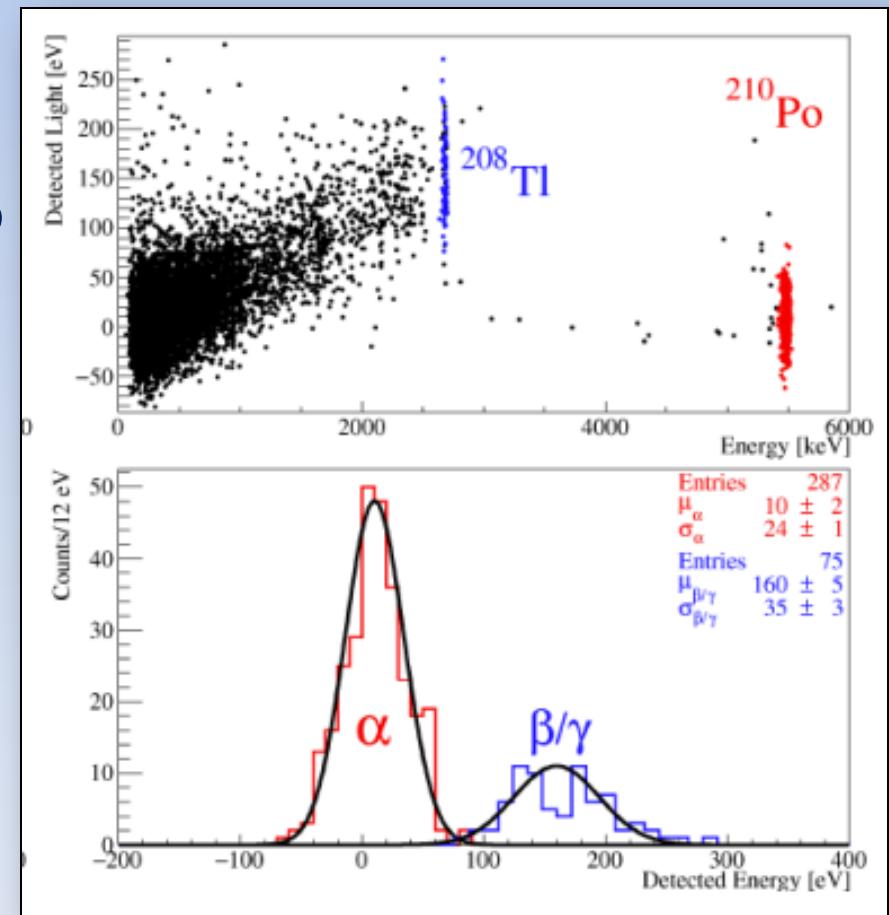
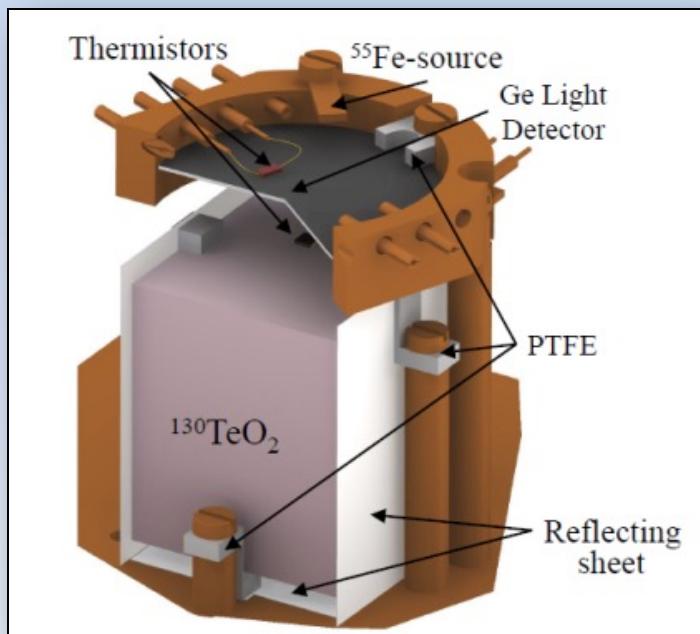
Light Detector:
Ge slab operated as bolometer

Main bolometer:
~470 g ZnSe crystal equipped
with NTD Ge thermistors

	Detector Mass [kg]	Isotopes	100 kg cost
ZnSe	664	2.4×10^{27}	~100 \$/g
ZnMoO ₄	540	1.3×10^{27}	~100 \$/g
TeO ₂	751	2.4×10^{27}	~17 \$/g

CUPID R&D

- CUORE limit expected from surface alpha contamination
- →CUORE Upgrade with Particle ID
- Observe Cerenkov light in addition to thermal signal



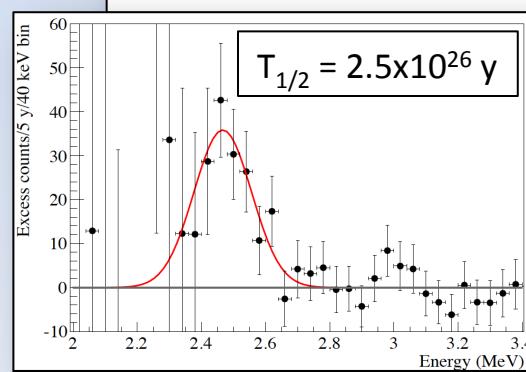
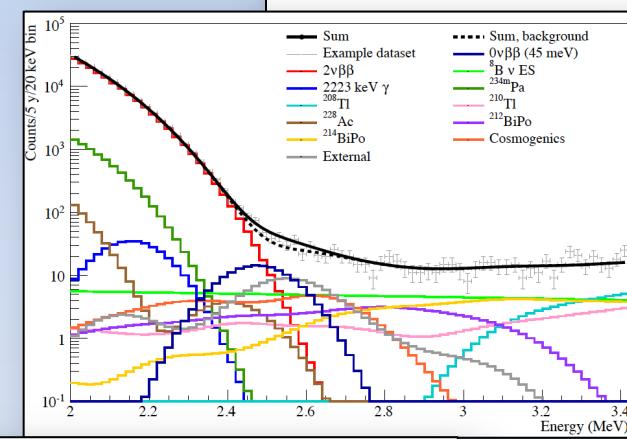
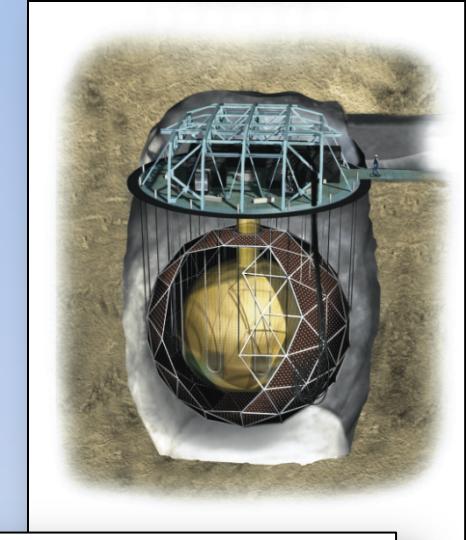
arXiv:1610.03513

SNO+ Phase II ^{130}Te

- 3% loading of Te already demonstrated
- Detector response model from Phase I predicts Phase II response
- Plug-in replacement of SNO+ PMTs with R5912-HQEs more than doubles light yield for Phase II Additional wavelength-shifter R&D could further improve this
- Containment bag R&D necessary to achieve cleanliness?

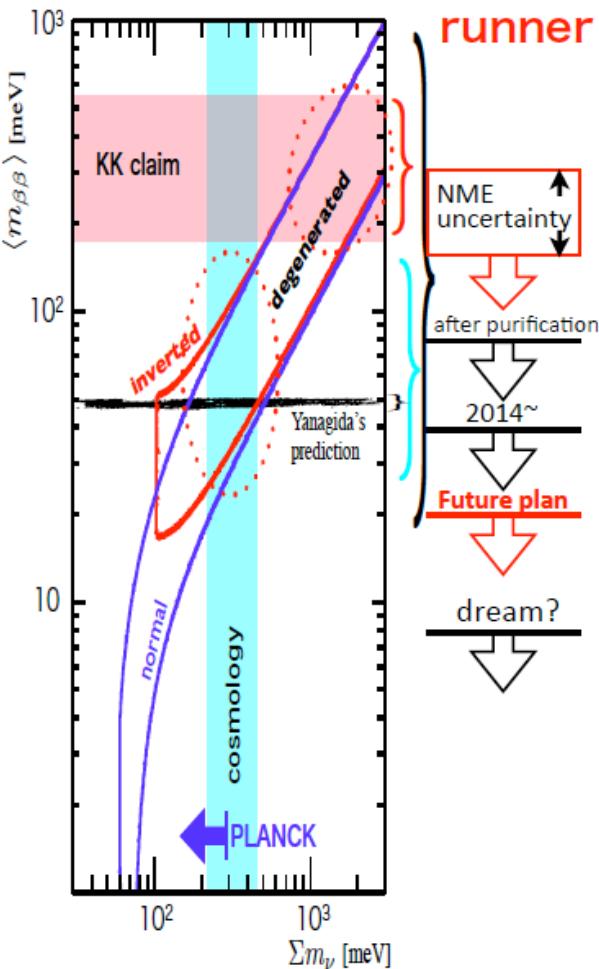
Can leverage KamLAND-Zen and BOREXINO knowledge

Phase II: $T_{1/2} > 7 \times 10^{26} \text{ y}$ (90% CL, natural)
 $T_{1/2} > 10^{27} \text{ y}$ (90% CL, enriched)
 $T_{1/2} > 4 \times 10^{26} \text{ y}$ (3σ , natural)



KamLAND2-Zen

Prospects



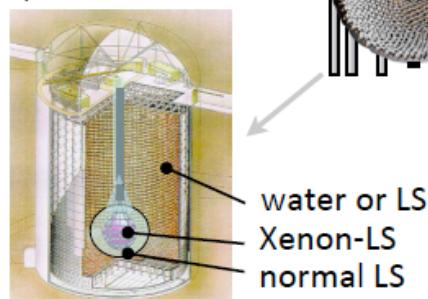
KamLAND-Zen is a top runner and being improved.

KamLAND-Zen 89.5 kg-yr
 $\langle m_{\beta\beta} \rangle < 160\text{--}330 \text{ meV}$ @90% C.L.
 the world best

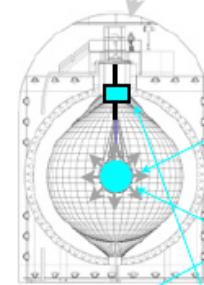
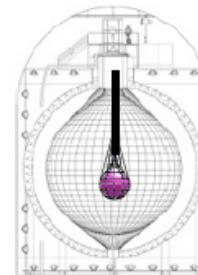
KamLAND-Zen 2nd phase (2013 fall -)
 100 times ^{110m}Ag reduction expected

KamLAND-Zen 600kg
 with clean mini-balloon

KamLAND2-Zen : high QE PMT, high yield LS, light concentrator
 $\sigma_E(2.6\text{MeV}) = 4\% \rightarrow < 2.5\%$
 Super-KamLAND-Zen



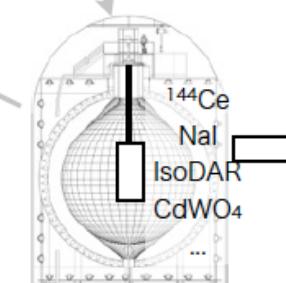
precision anti-neutrino physics
 $p \rightarrow v K^+$ is also possible.



R&D for pressurized Xe

R&D for scintillation film

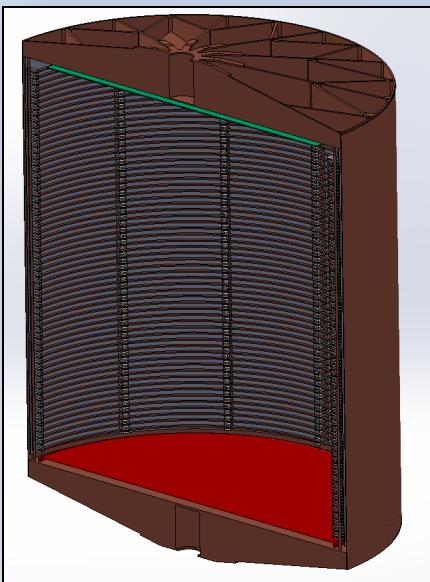
R&D for β / γ discrimination (high sensitivity imaging)



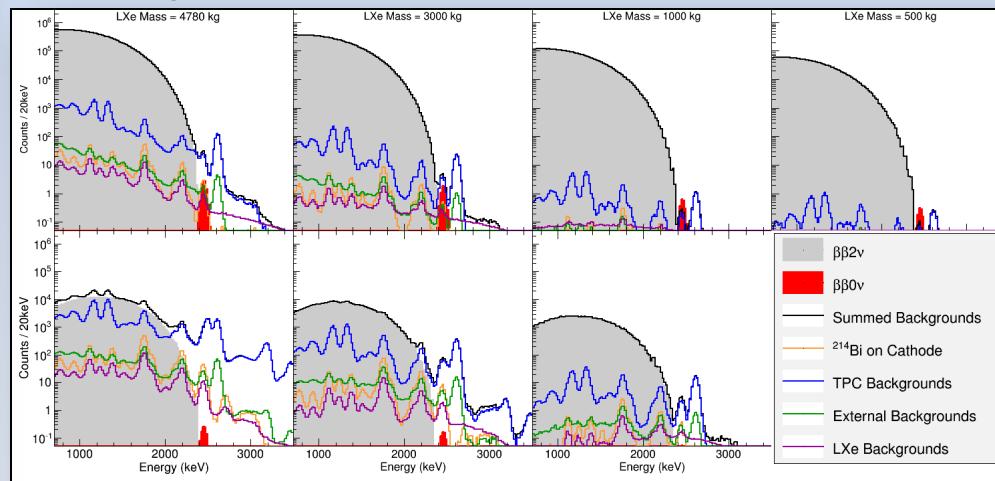
Various low BG measurement can be accommodated.

nEXO ^{136}Xe

- 5 tonnes of enrXe
- nEXO 5 yr 90% CL sensitivity: $T_{1/2} > 6.6 \cdot 10^{27}$ yr
- Lxe homogeneous imaging TPC similar to EXO---200:
 - Baseline: install at SNOLAB (cosmogenic background reduced wrt EXO---200)
 - Simultaneous measurement: energy, spatial extent, location, particle ID
 - Multi---parameter approach improves sensitivity: strengthens proof in case of discovery
 - Inverted hierarchy covered with a well proven detector concept
 - Possible later upgrade for Ba retrieval/tagging: start accessing normal hierarchy



Deeper into fiducial volume →



Single---site:
Mainly
signal,
2v and 0v

Multi---site:
Mainly
background

Summary

- Significant experimental progress in the last decade
 - Multiple experiments have attained sensitivities of $T_{1/2} > 10^{25}$ years.
 - In the next few years expect to reach sensitivity exceeding $T_{1/2} > 10^{26}$ years.
 - Major advances in development of ultra-clean low activity materials and assay capabilities.
- Large international collaborations are moving forward with designs for next generation experiments based on lessons learned from the current measurements.
 - All aim for sensitivity and discovery levels at $T_{1/2} > 10^{27}$ years
 - An improvement of $\times 100$ over current results.
- The field is rapidly approaching readiness to proceed with tonne scale experiments.

Thanks to J. Wilkerson, G. Gratta, J. J. Gomez-Cadenas, B. Fujikawa, and many others